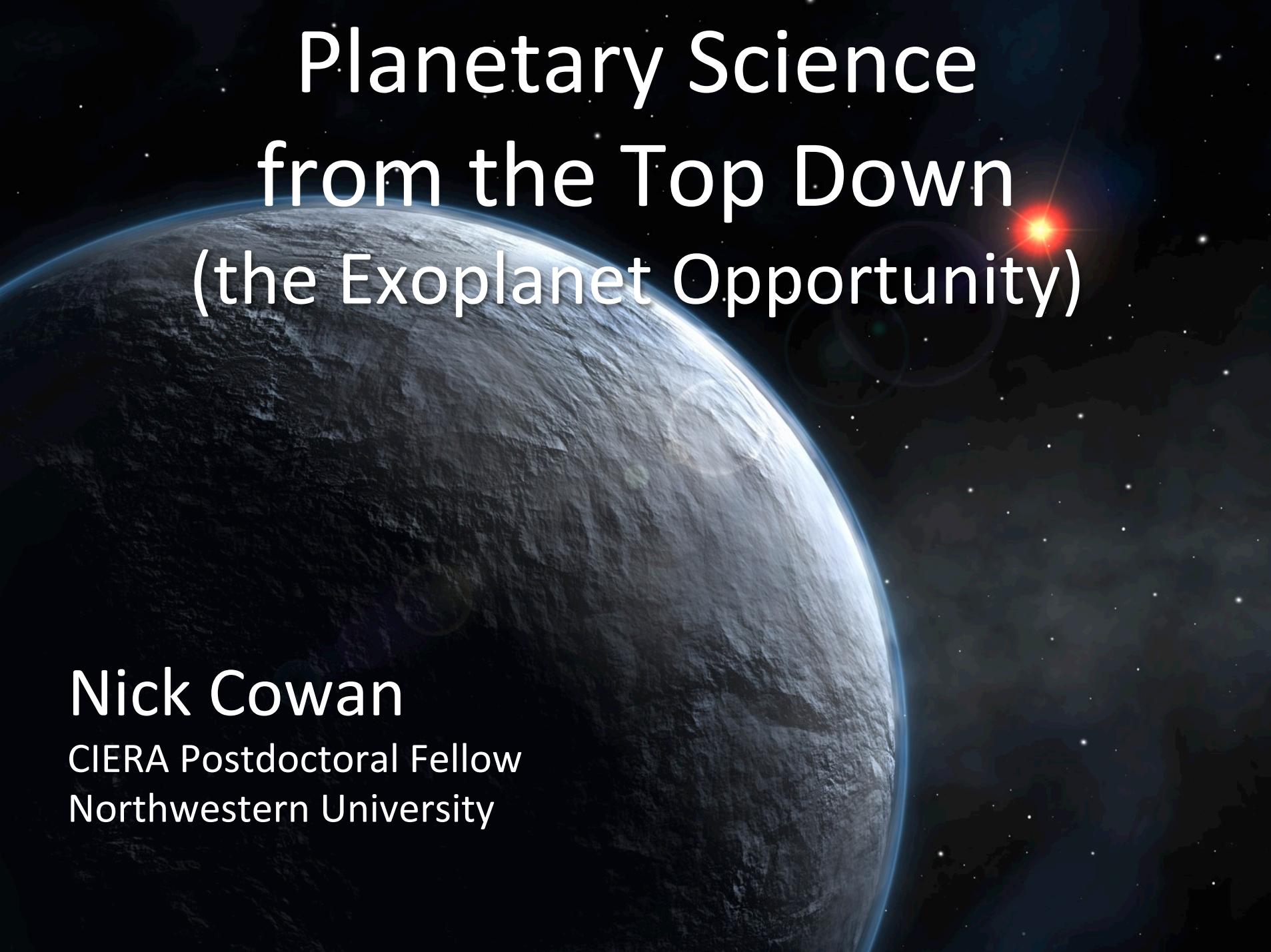
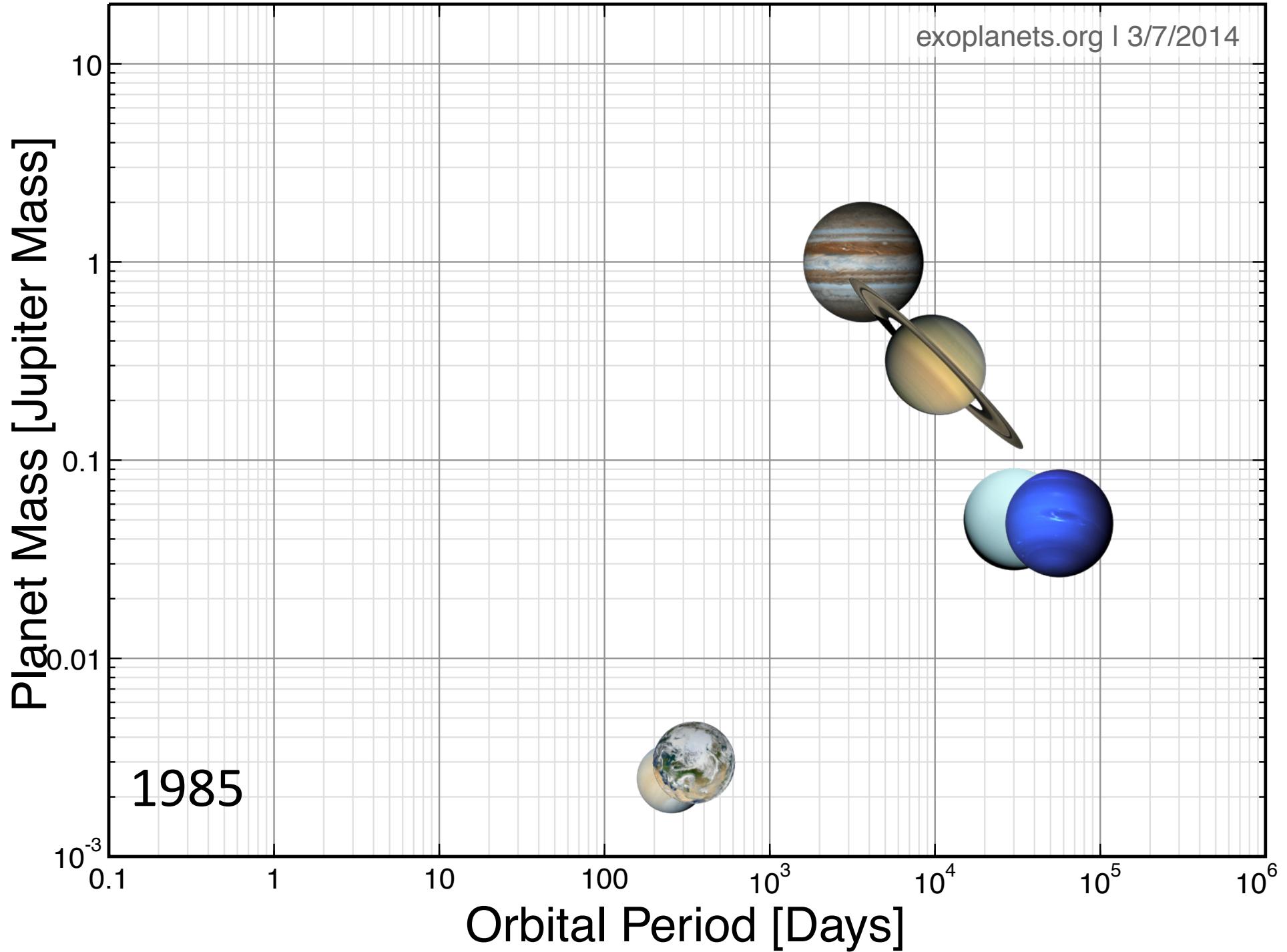


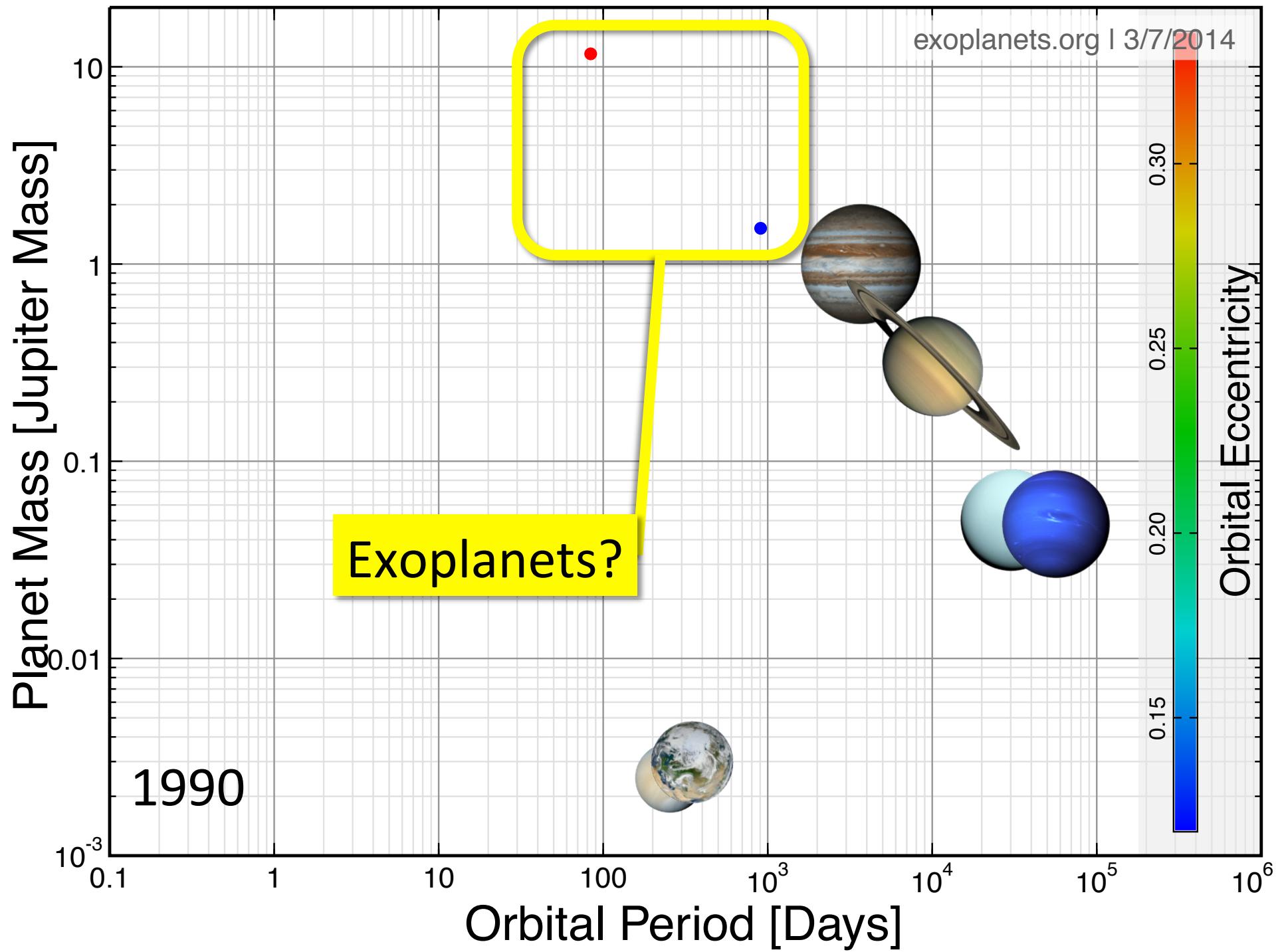
# Planetary Science from the Top Down (the Exoplanet Opportunity)

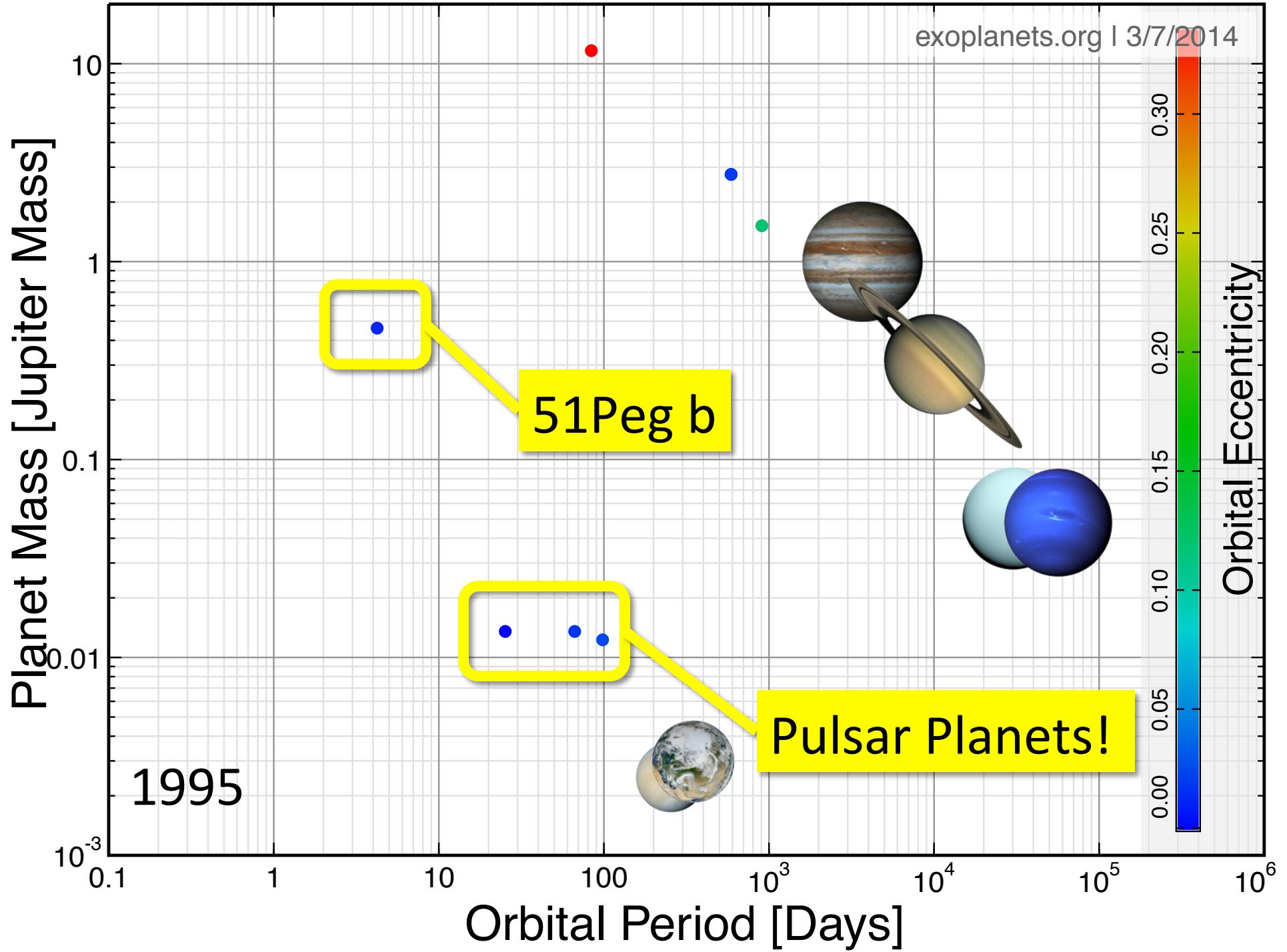


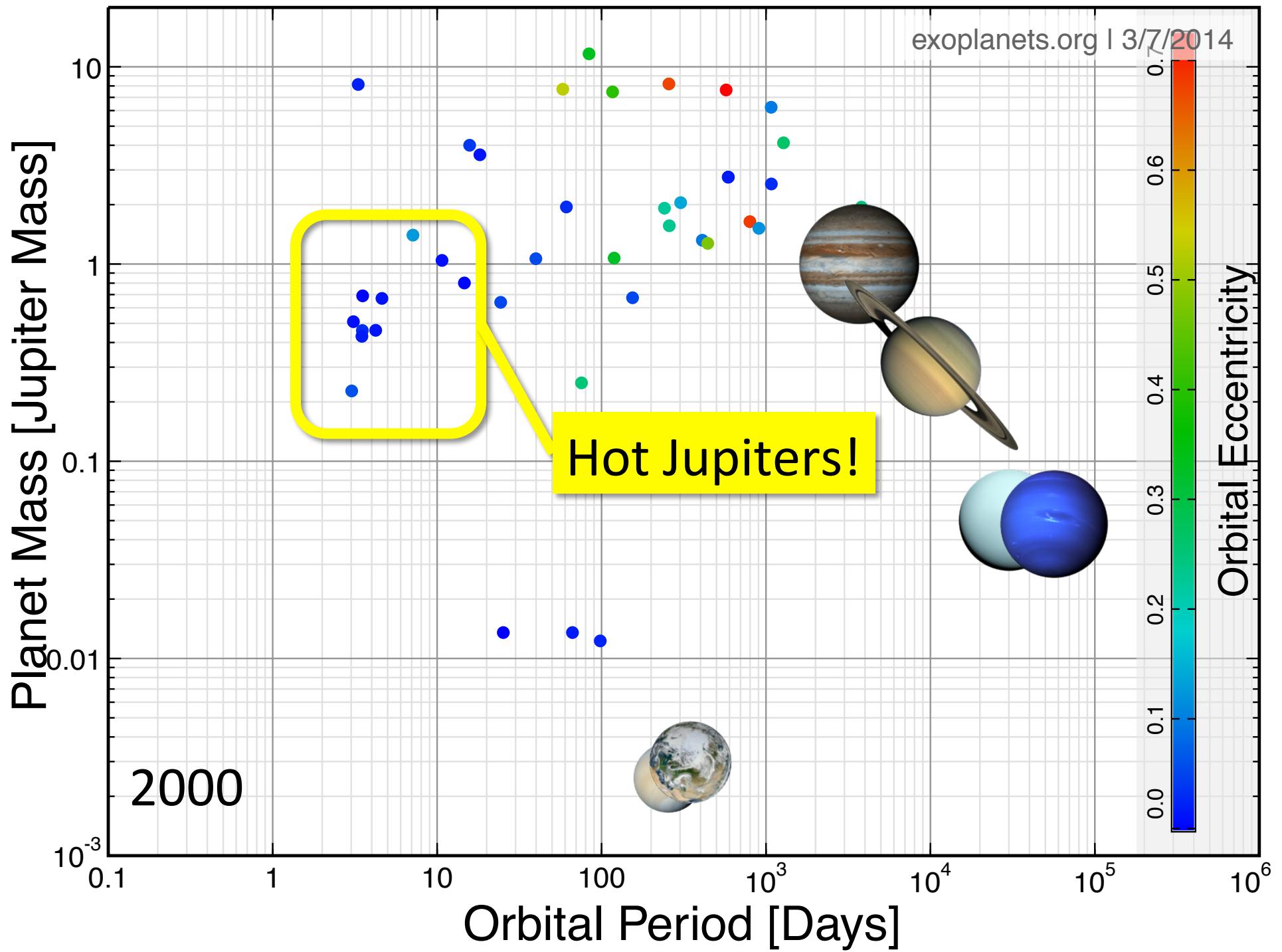
Nick Cowan

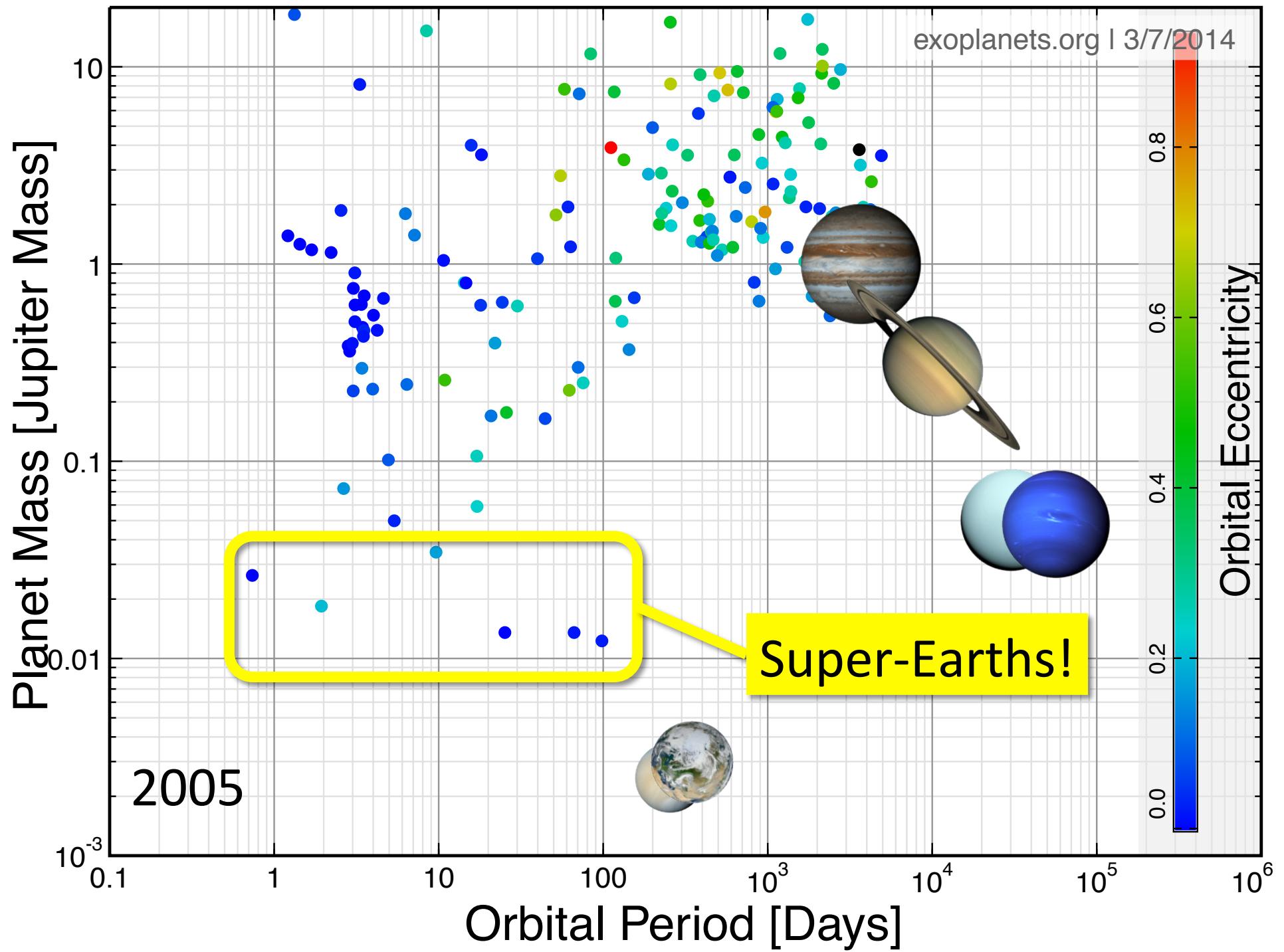
CIERA Postdoctoral Fellow  
Northwestern University

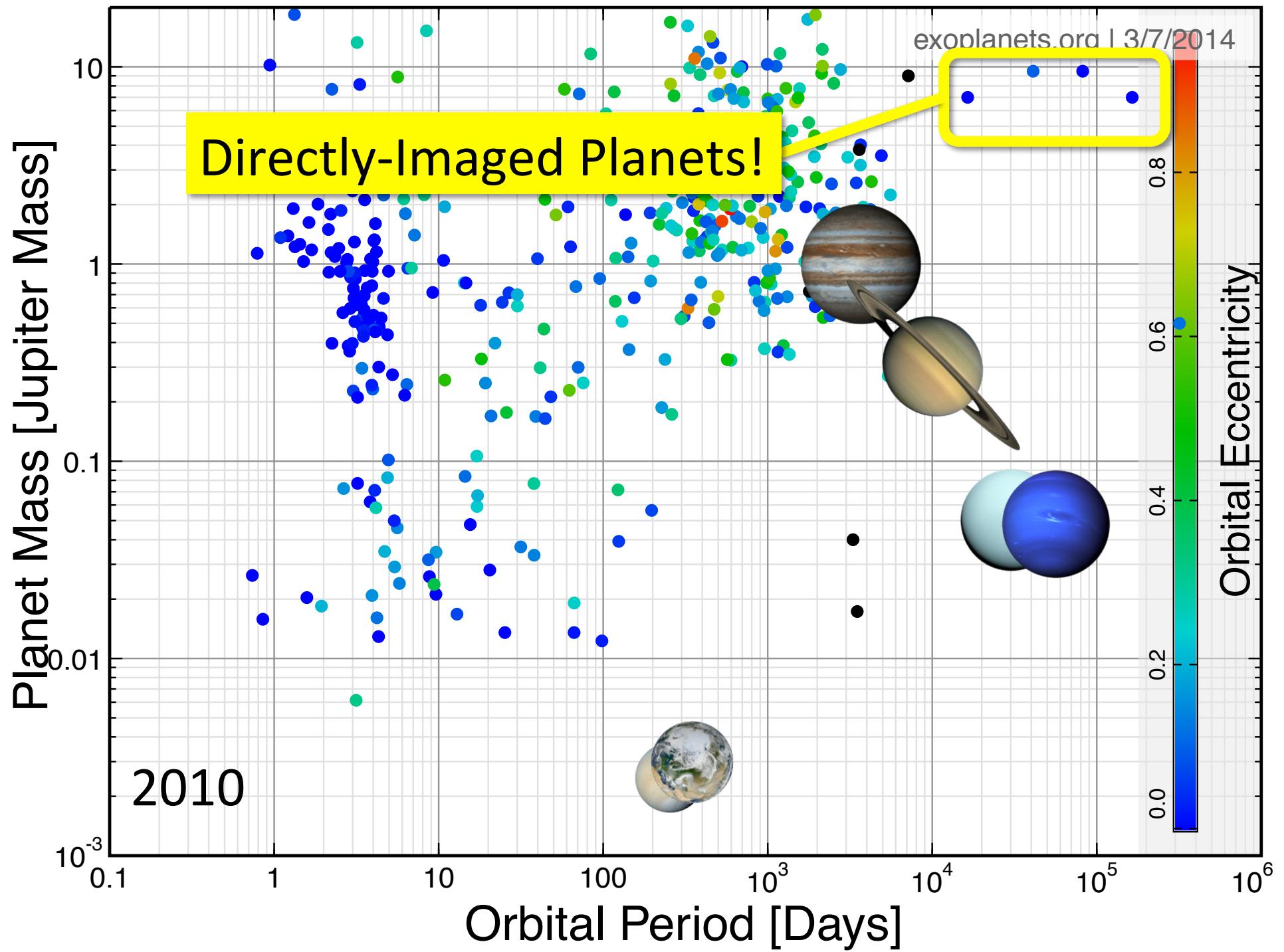


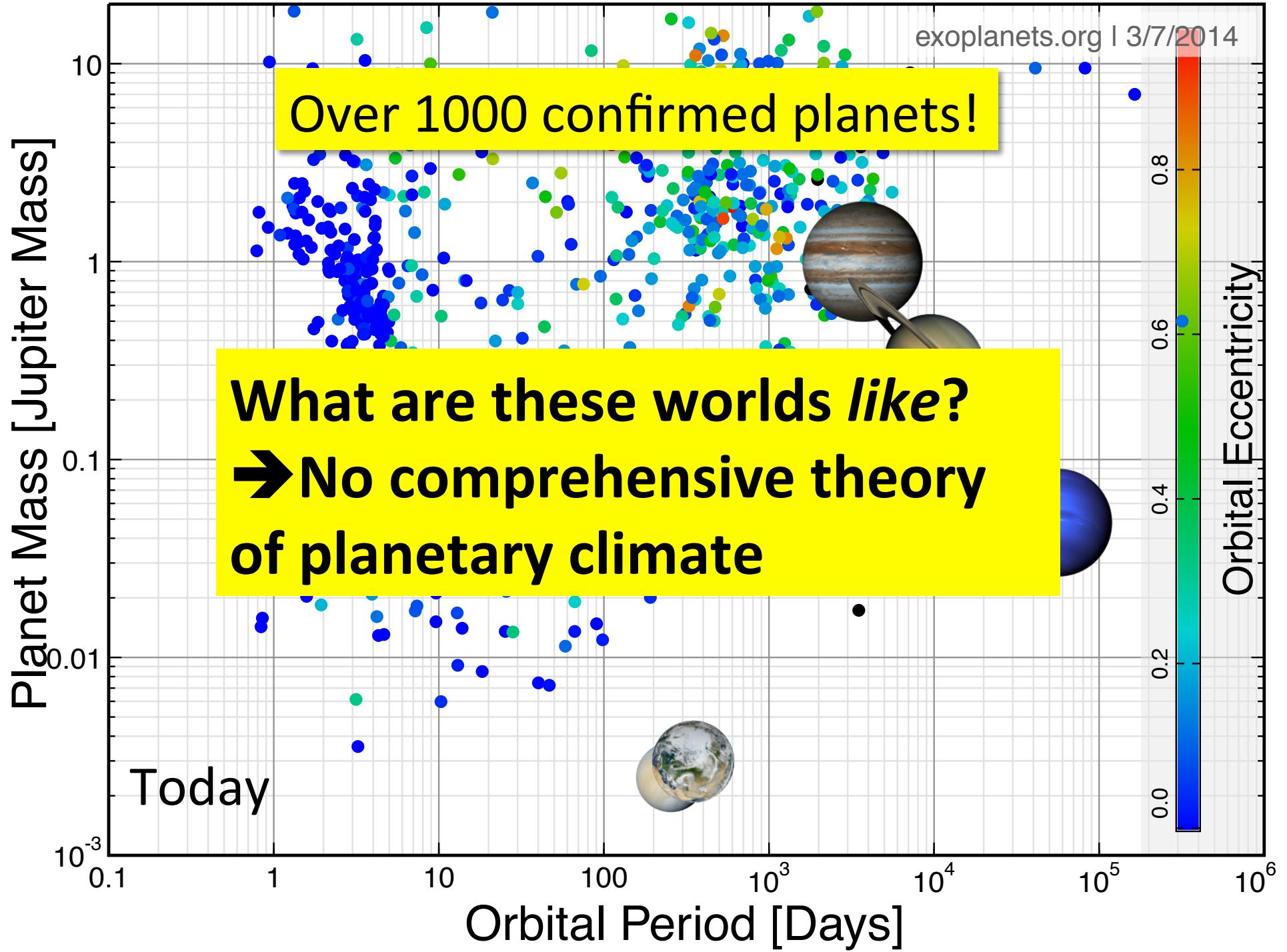




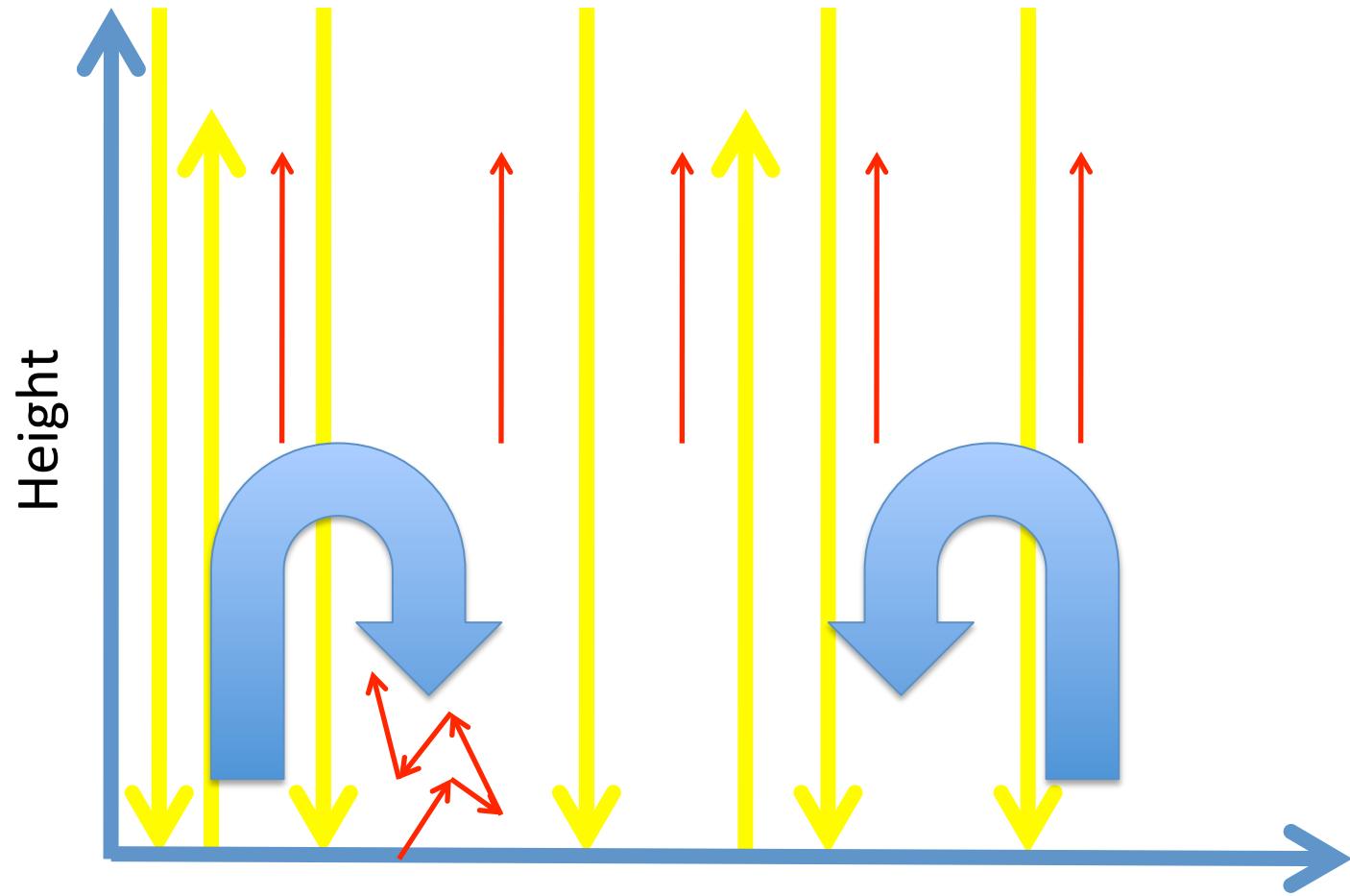




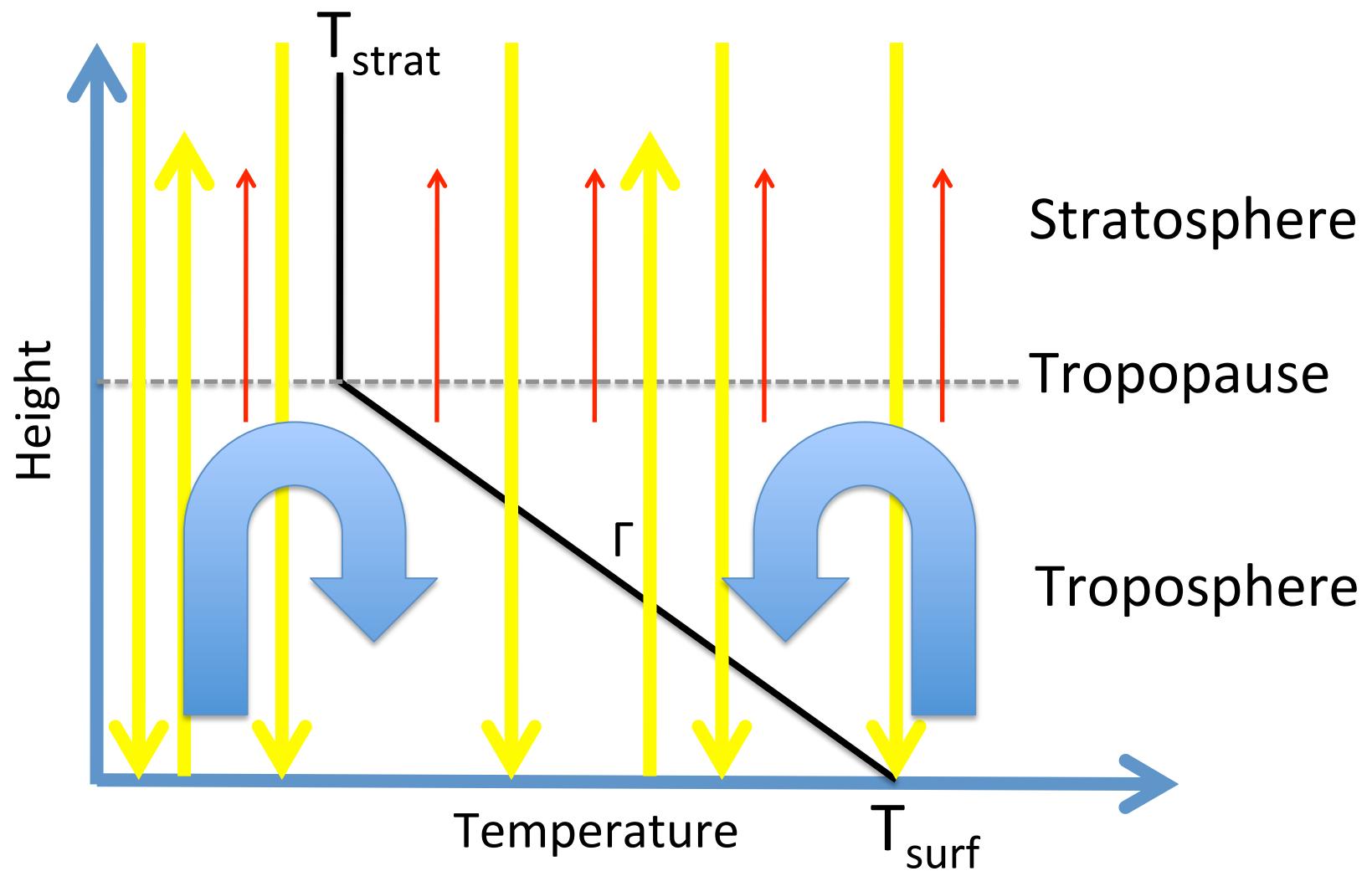




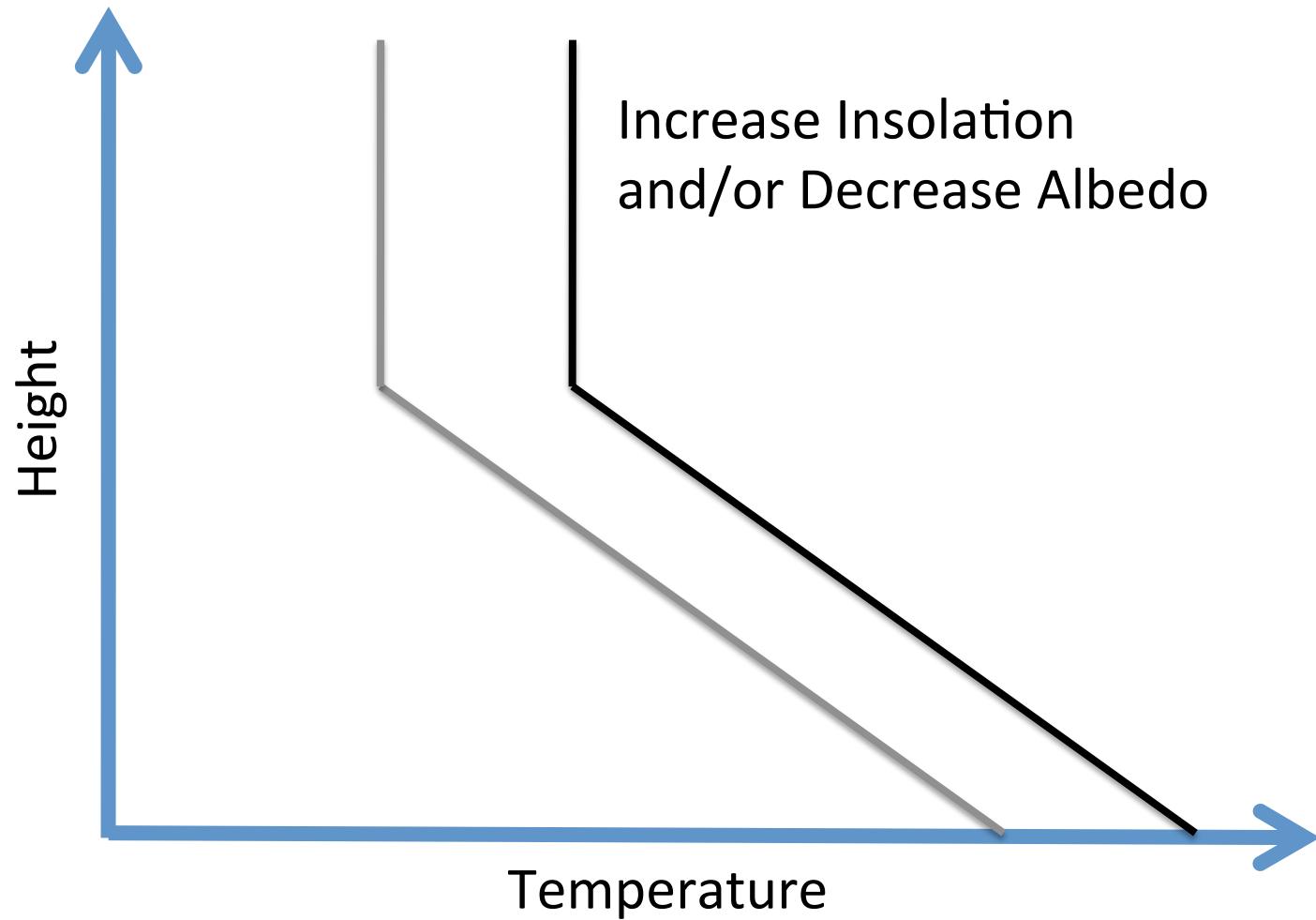
# 1D Climate Cartoon



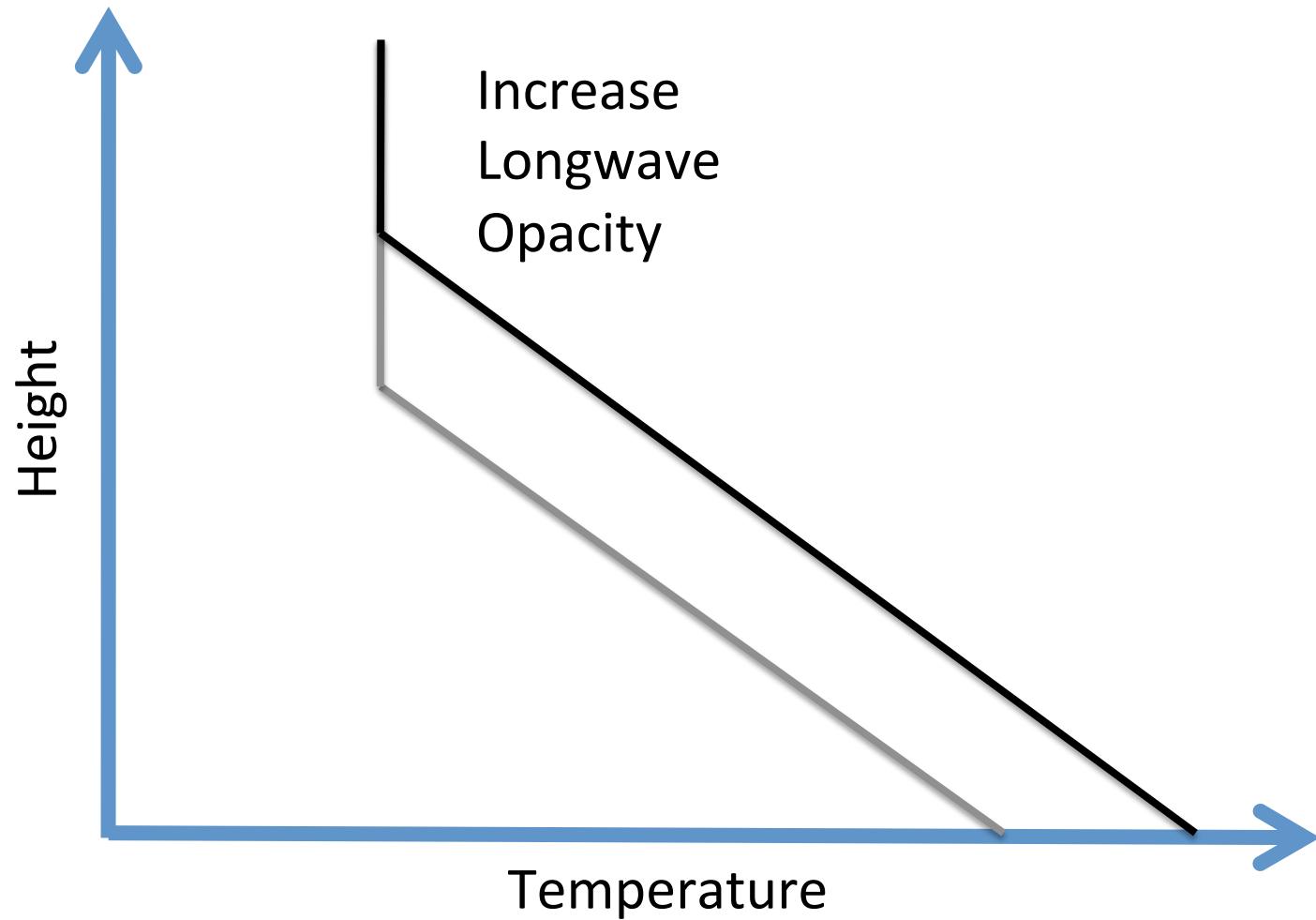
# 1D Climate Cartoon



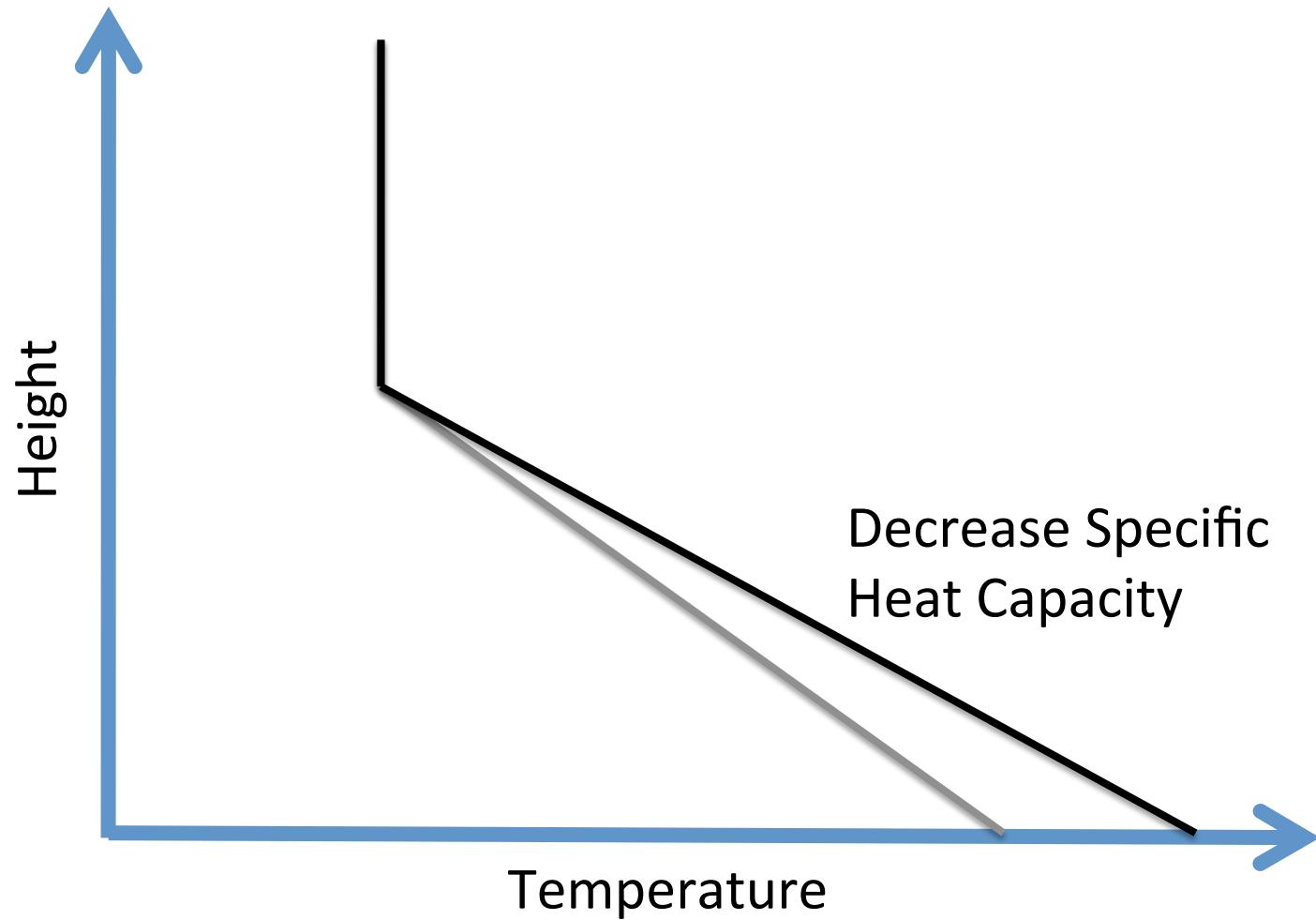
# 1D Climate Cartoon



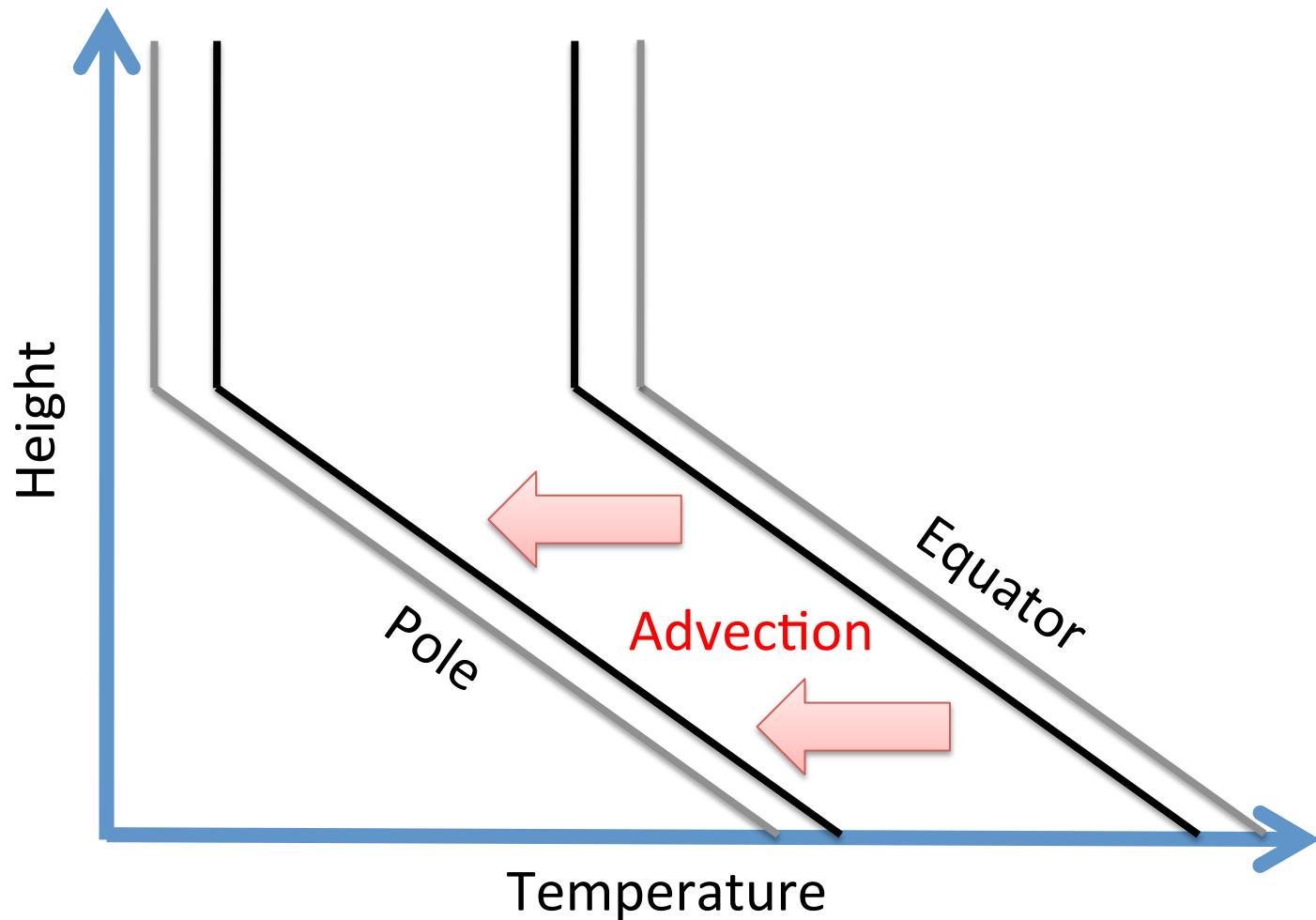
# 1D Climate Cartoon

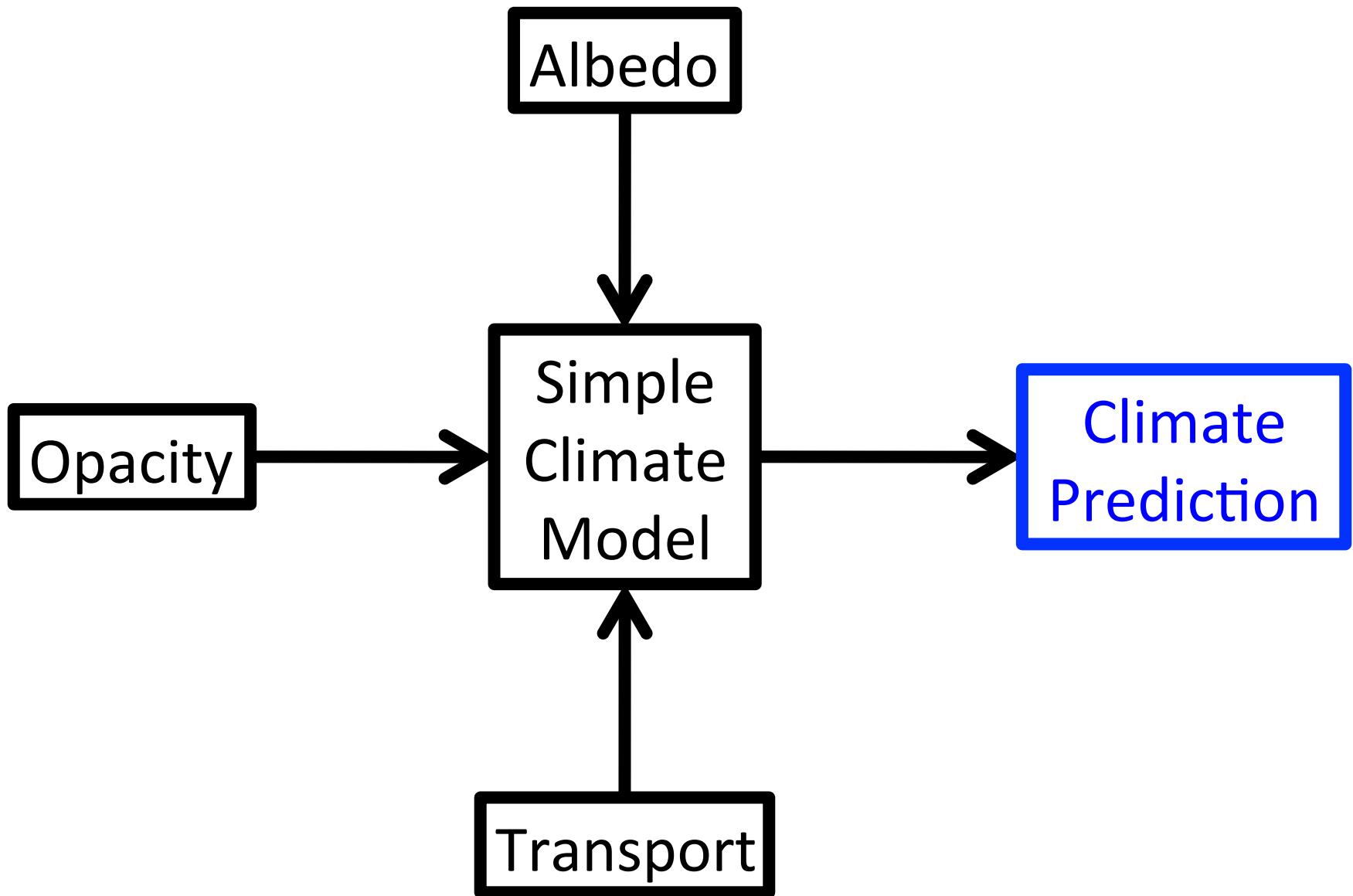


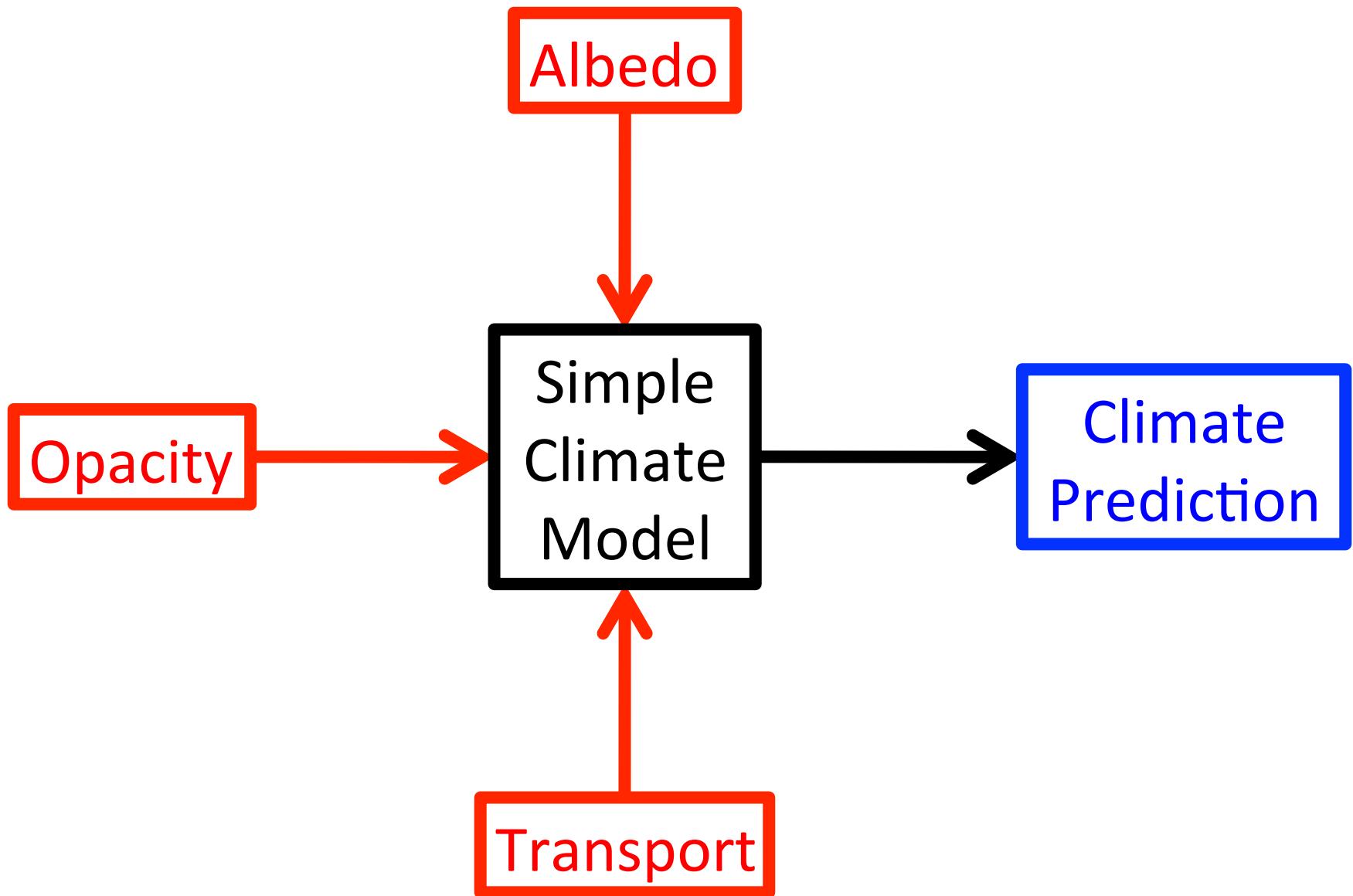
# 1D Climate Cartoon

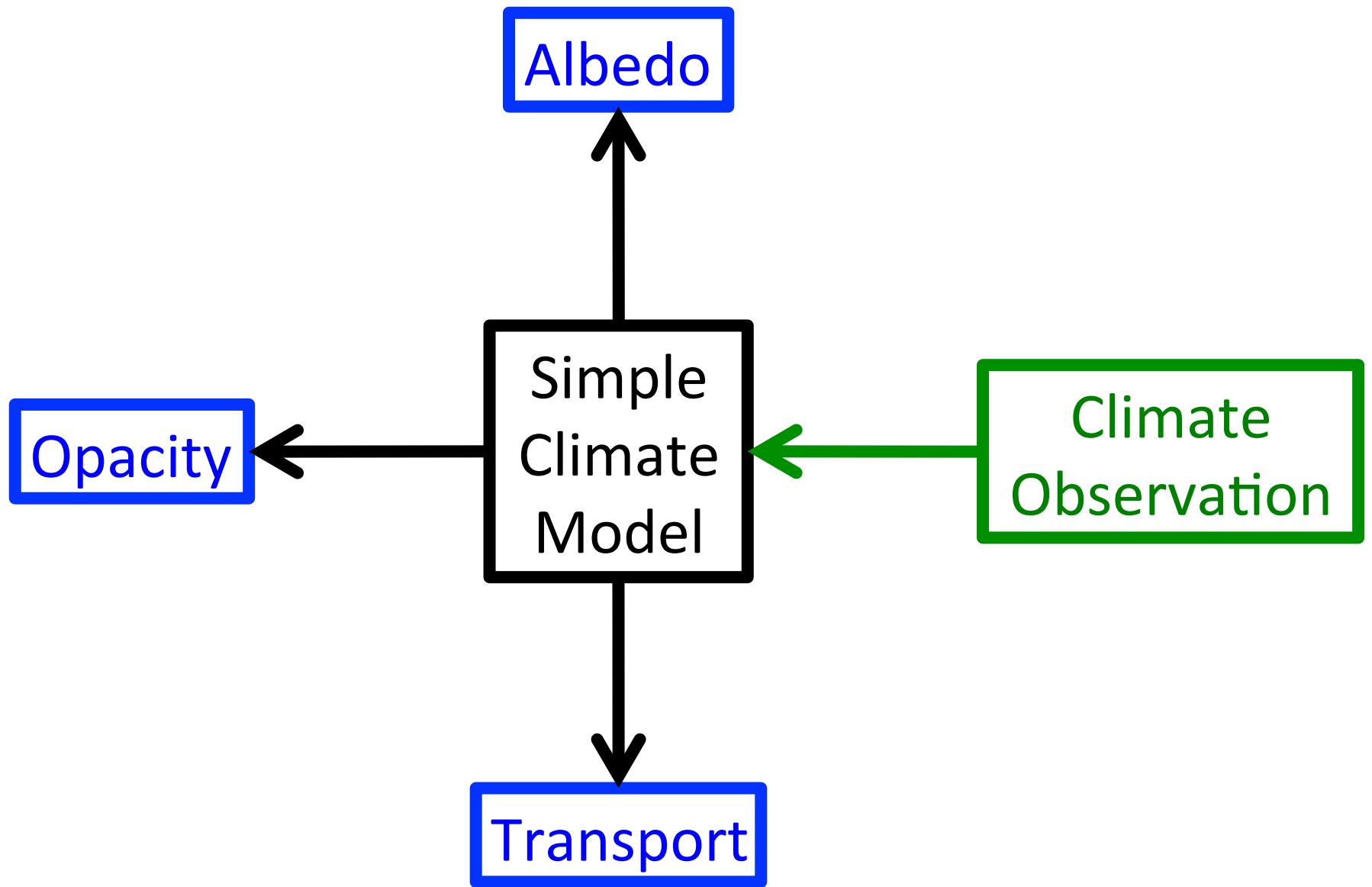


# 2D Climate Cartoon (eg: height + latitude)

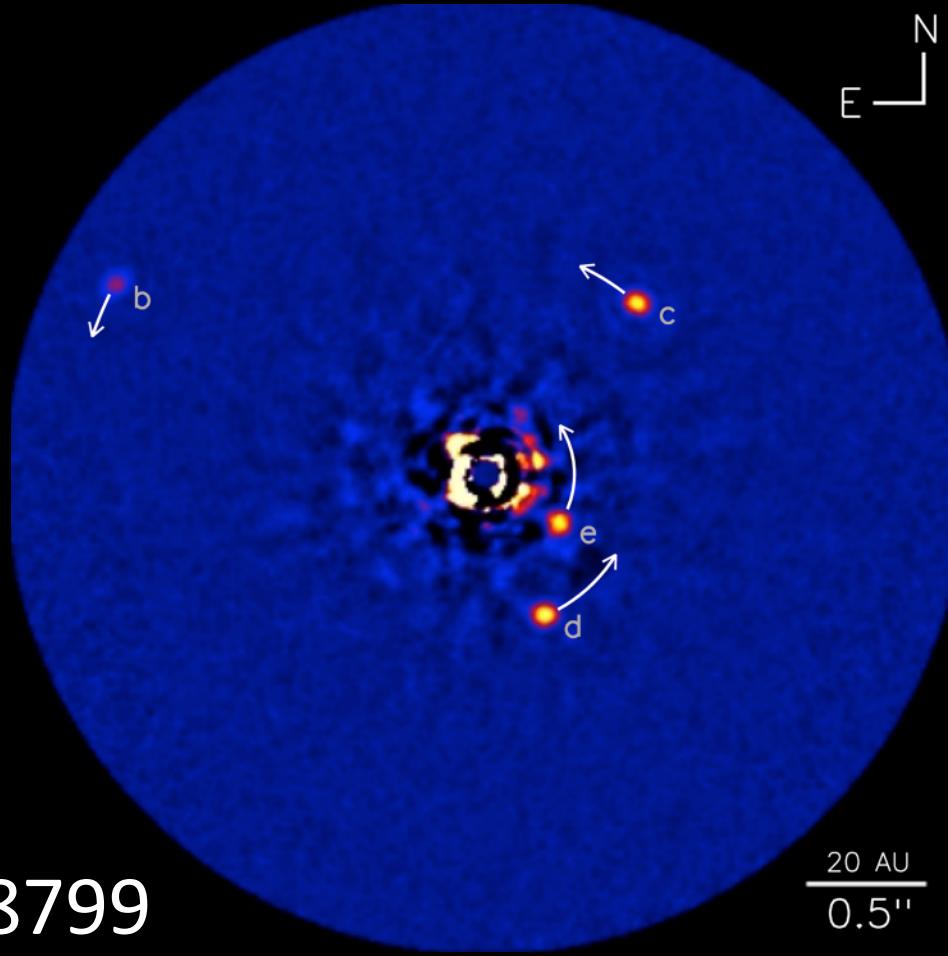




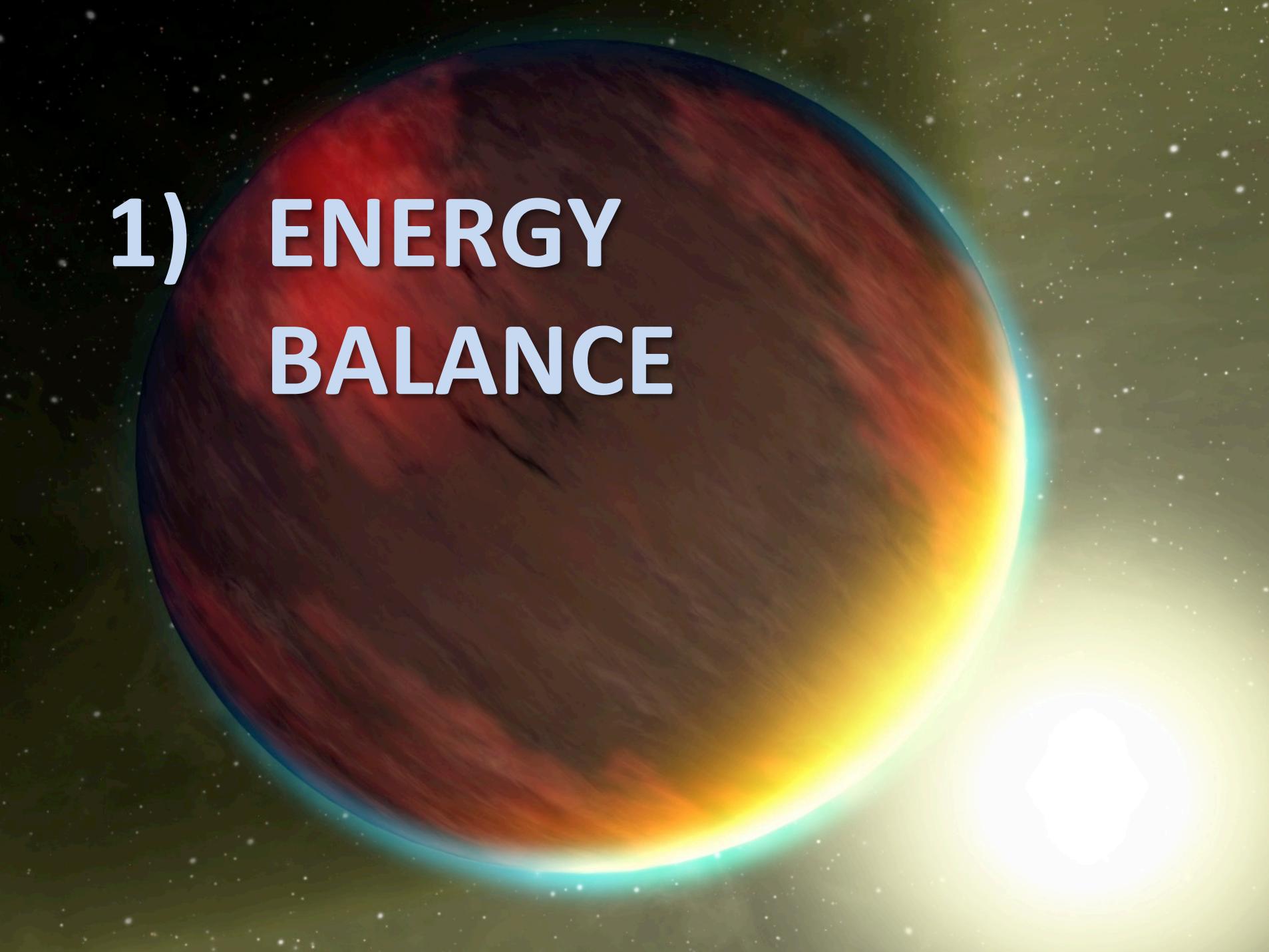




# Problem: Exoplanets are Far Away

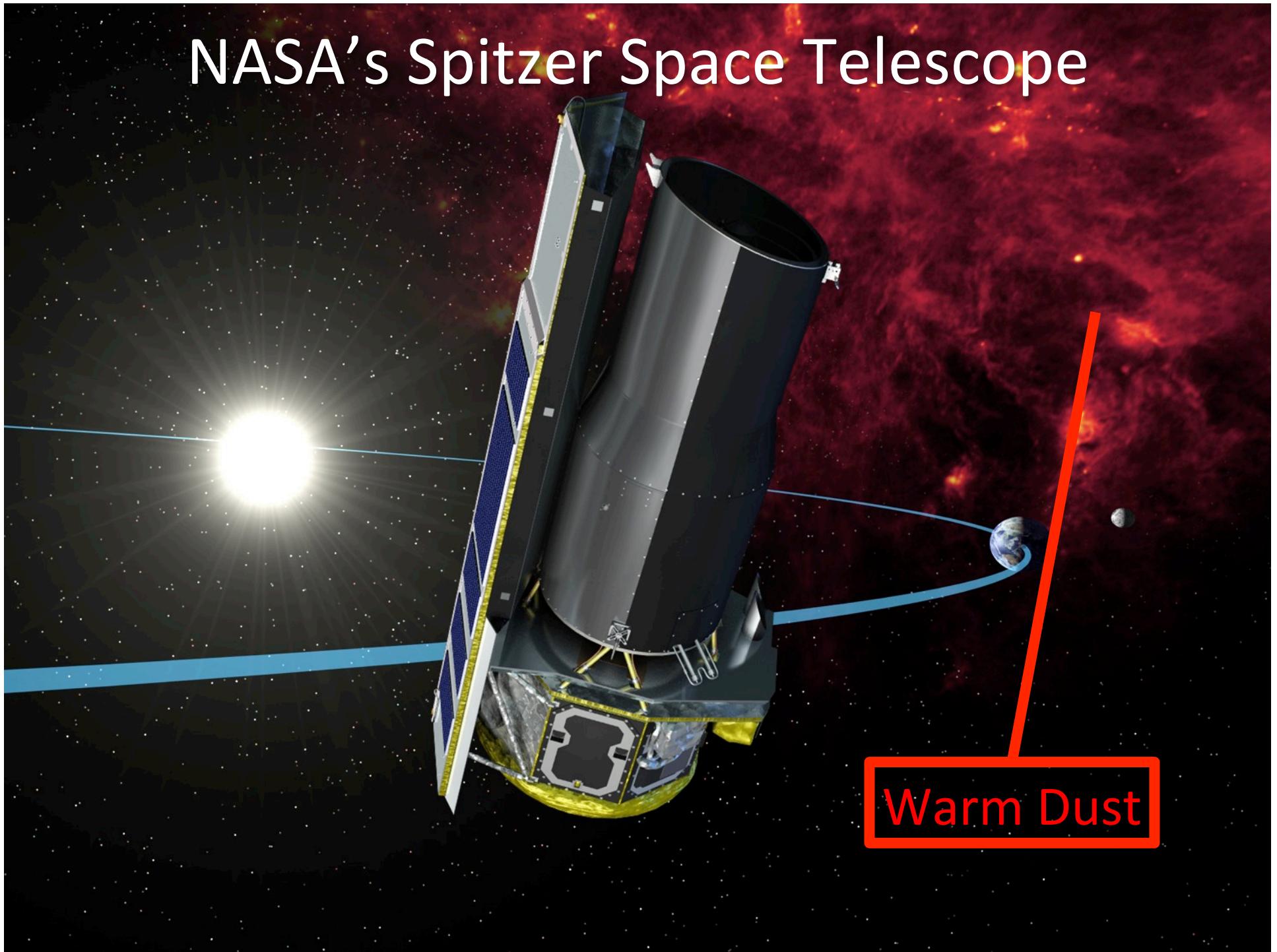


Marois+ (2010)



# 1) ENERGY BALANCE

# NASA's Spitzer Space Telescope

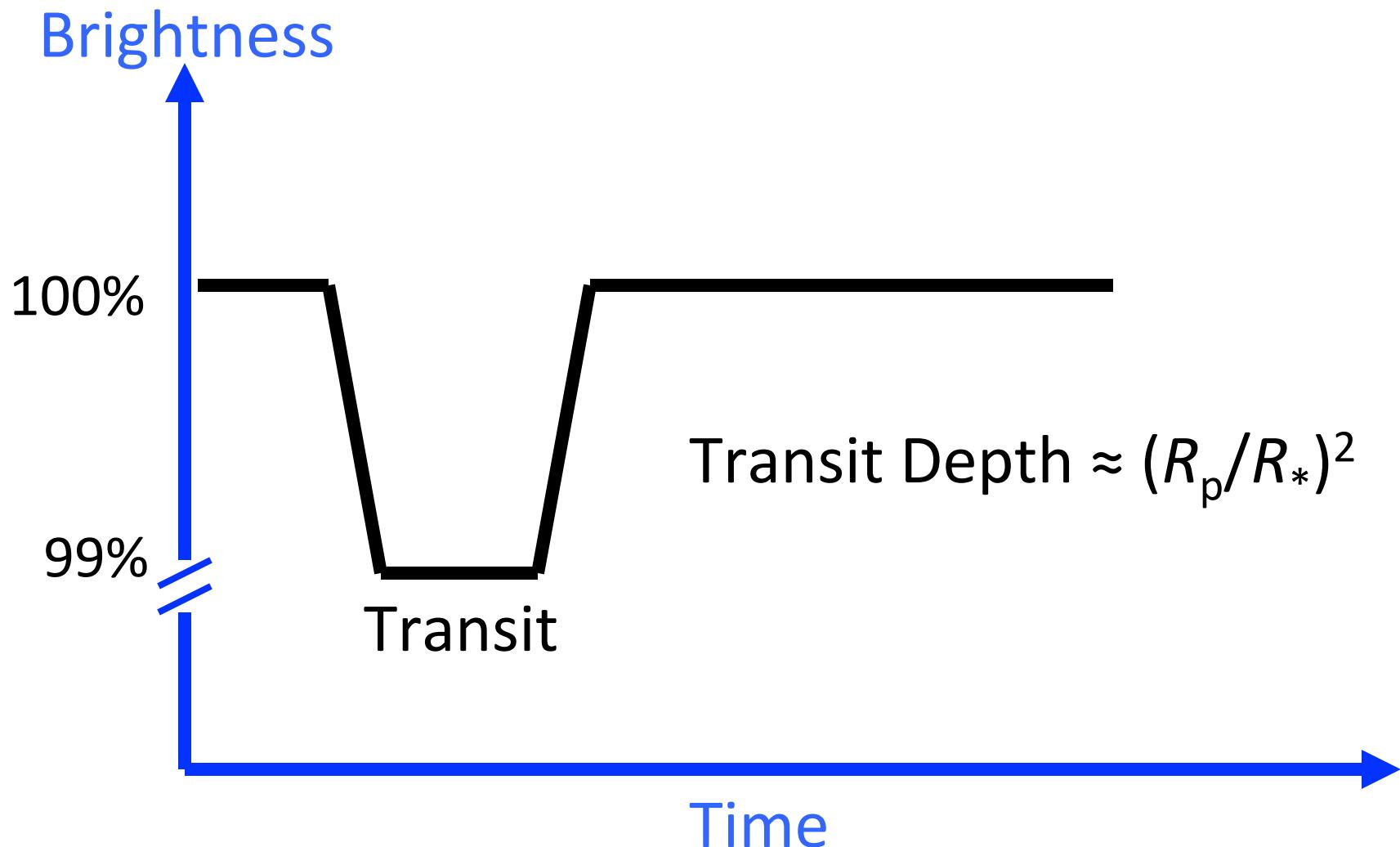


Warm Dust

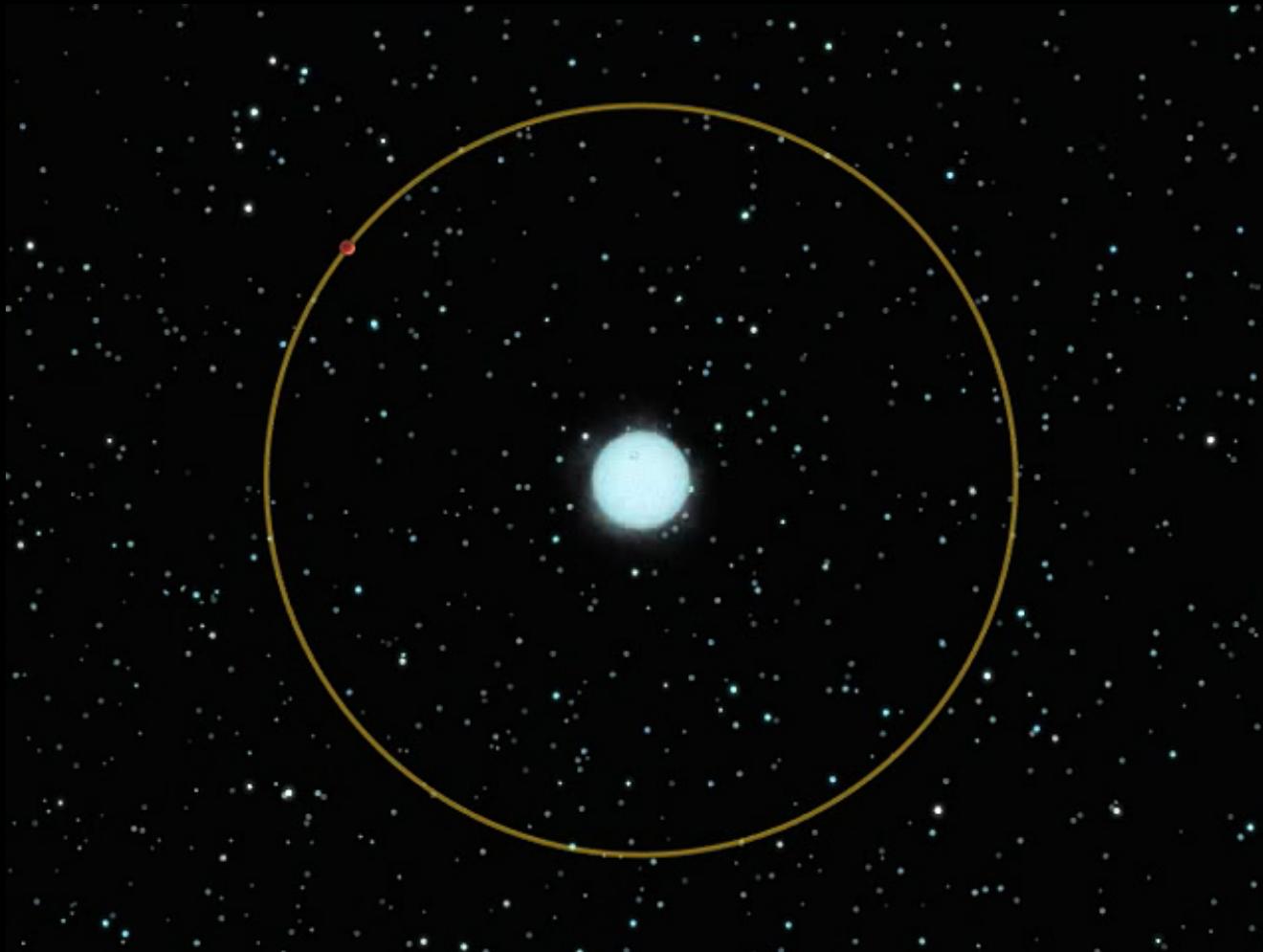
# Transit



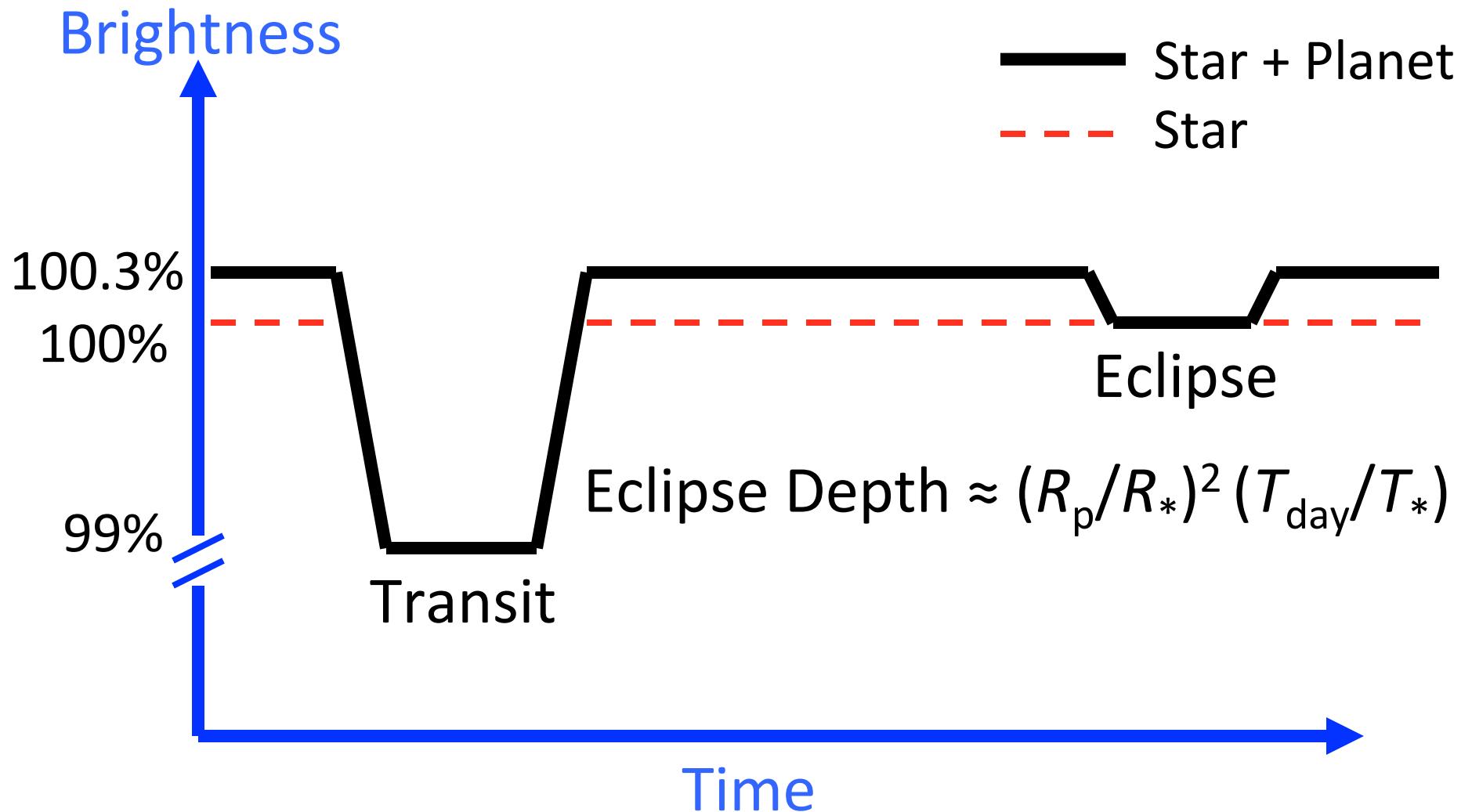
# Transit Lightcurve



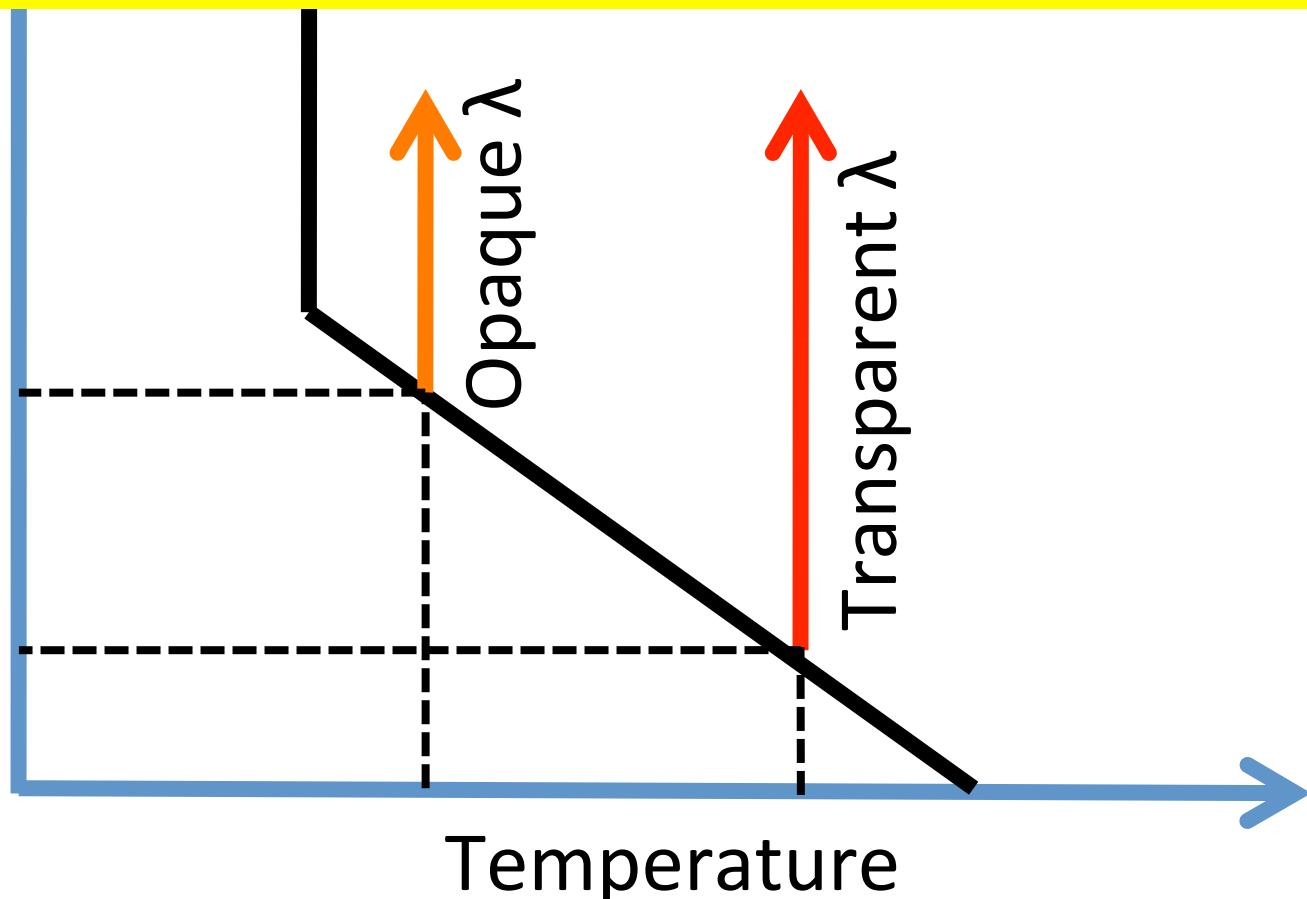
# Thermal Eclipse



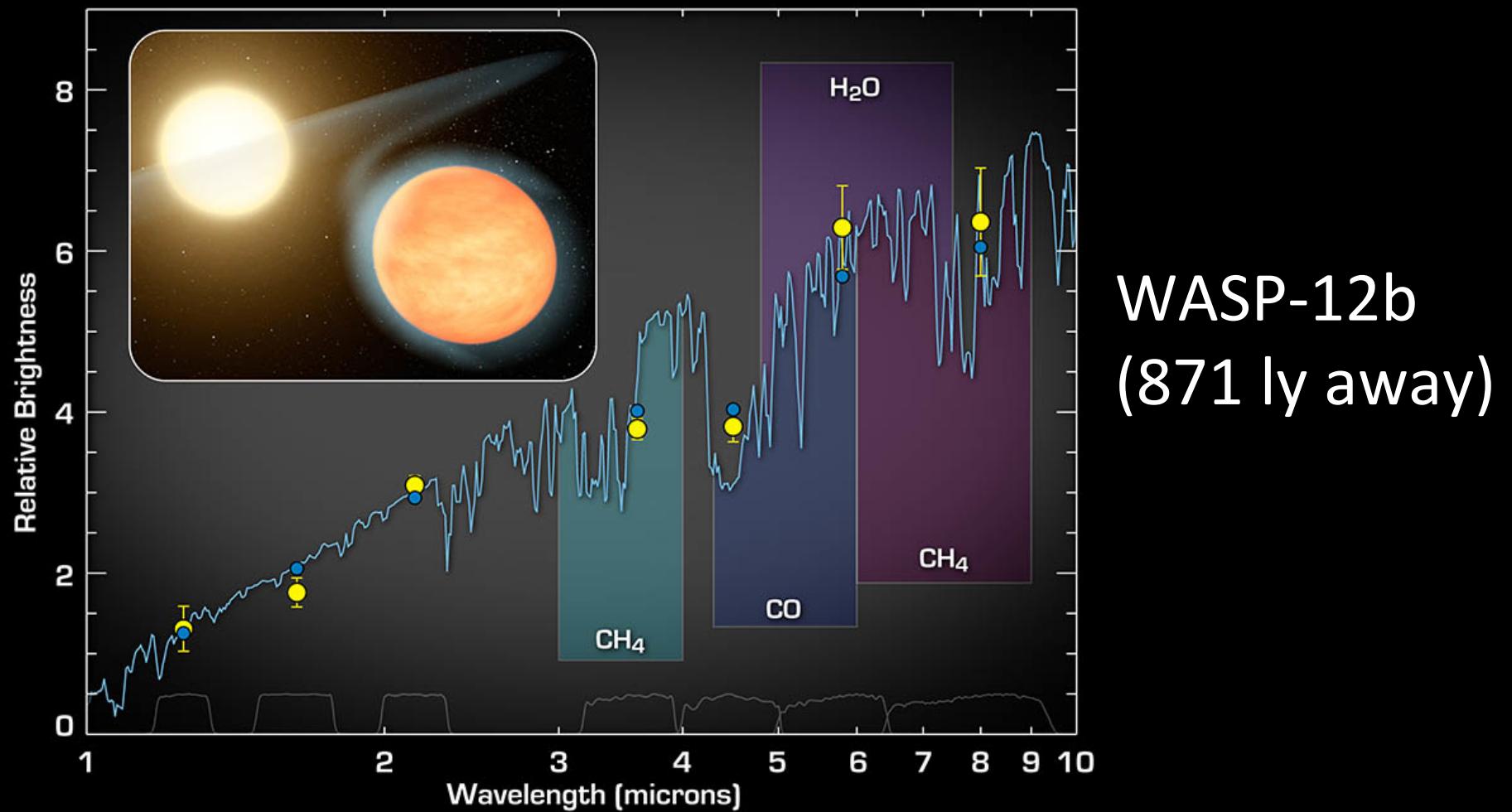
# Eclipse Light Curve



- (1) Opacity Depends on Wavelength
  - (2) Emitting Layer Depends on Opacity
  - (3) Temperature Depends on Height
- Brightness Depends on Wavelength



# Emission Spectrum → Molecules & Temperature Profile



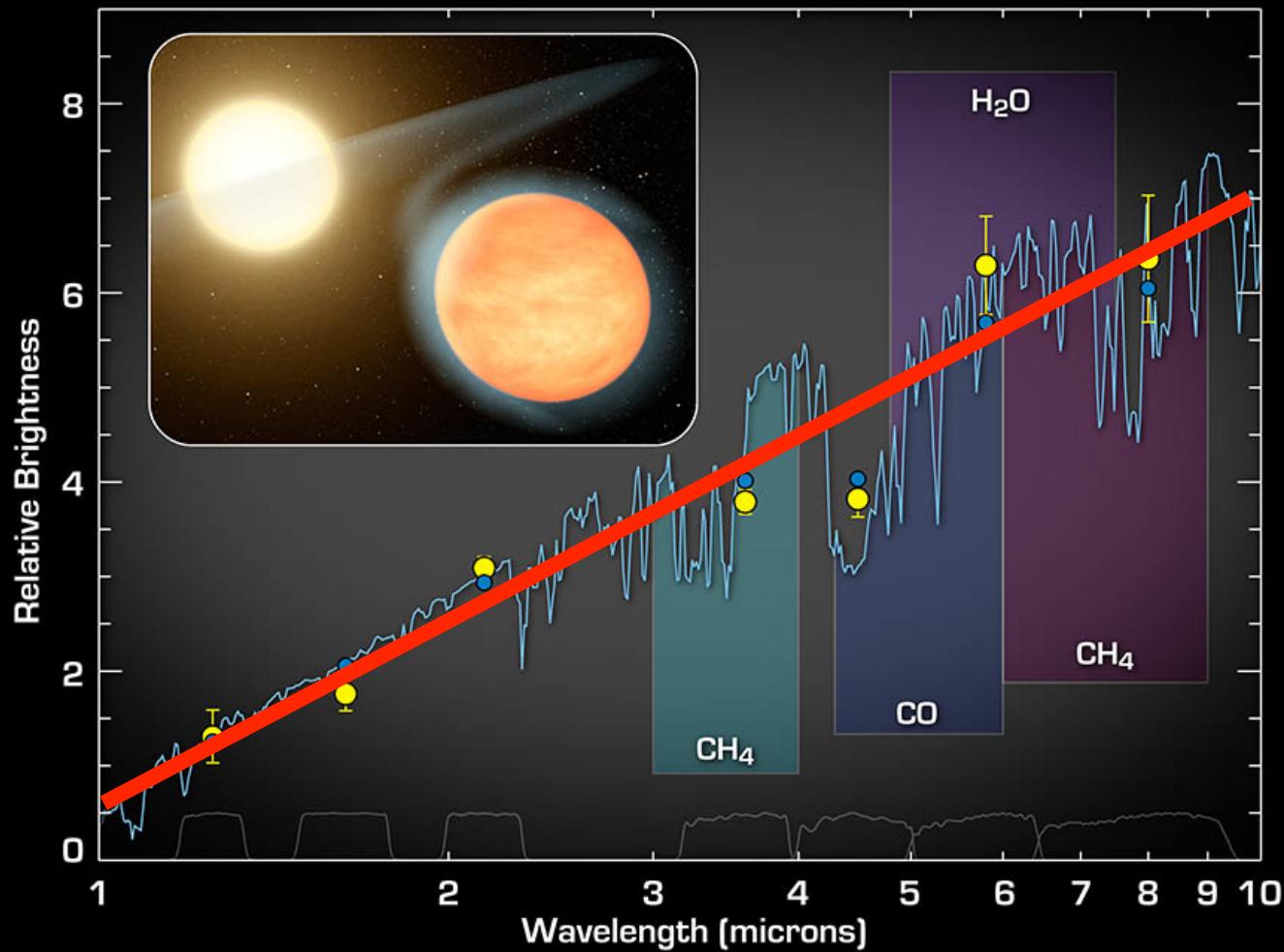
Exoplanet WASP-12b

NASA / JPL-Caltech / N. Madhusudhan (Princeton University)

Spitzer Space Telescope • IRAC

ssc2010-10a

# Hot Jupiters have Featureless Broadband Spectra (Hansen, Schwartz & Cowan 2014)

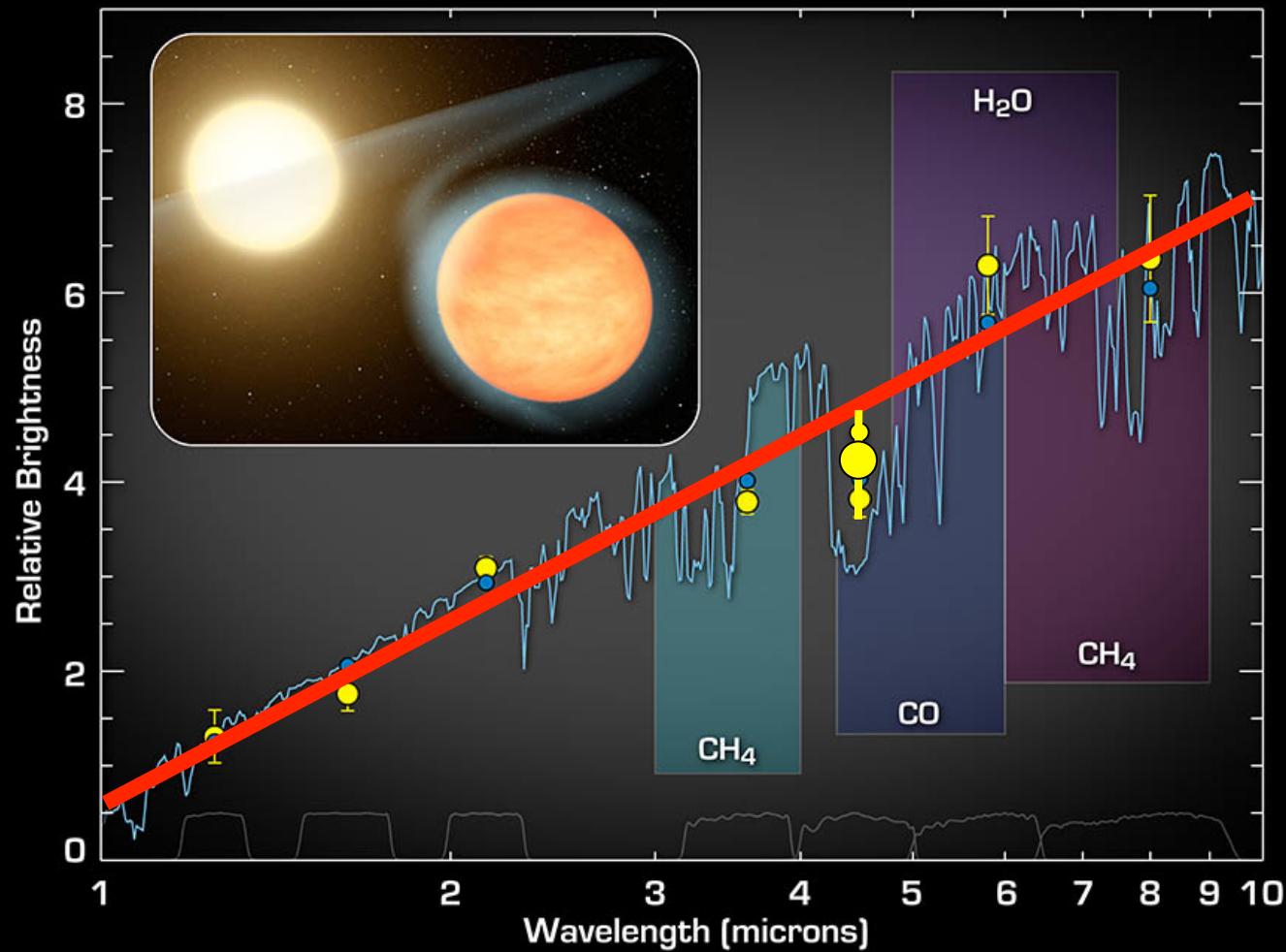


- 43 planets with multi-band eclipse photometry
- 7/43 exhibit evidence of spectral features  
(Spectral Retrieval\* BIC < Blackbody BIC)

**(1) When measurements are few, simple models do well**

\*Idealized Model with  $\chi^2=0$

# Hot Jupiters have Featureless Broadband Spectra (Hansen, Schwartz & Cowan 2014)



Exoplanet WASP-12b

NASA / JPL-Caltech / N. Madhusudhan (Princeton University)

Spitzer Space Telescope • IRAC

ssc2010-10a

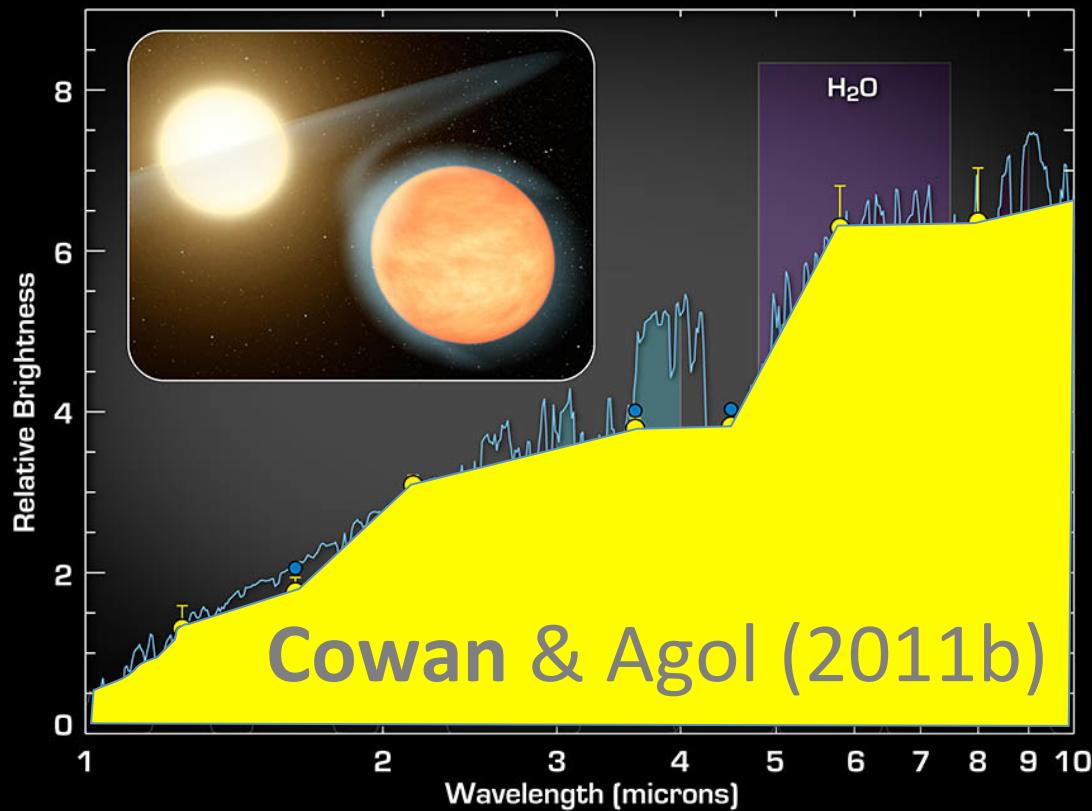
- BUT single-eclipse depths have not been repeatable to better than  $4.5 \times 10^{-4}$ 
  - OR errors have been under-estimated by  $2 \times$
- Reanalyses of *same* data *are* repeatable
  - Repeated eclipses *analyzed in unison* are good to  $< 10^{-4}$

**(2) When data are self-calibrated,  
large data-sets are good**

- Adopting realistic uncertainties for single-eclipse measurements, NO planets currently show evidence of spectral features
- The broadband spectra poorly fit by blackbodies are also poorly fit by radiative transfer models

**(3) “Spectral Features” may be noise**

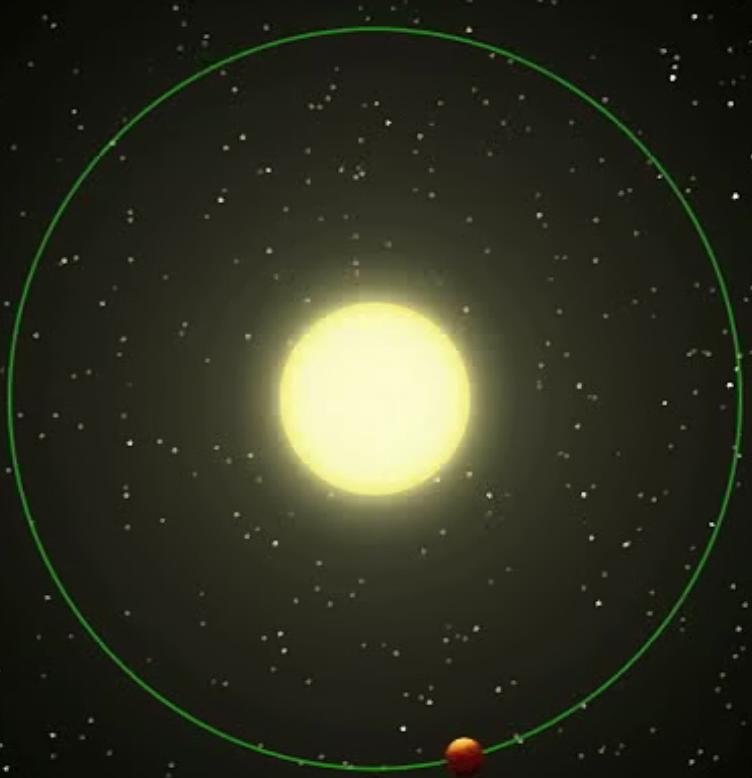
# Emission Spectrum → ~~Molecules & Temperature Profile~~ Effective Temperature



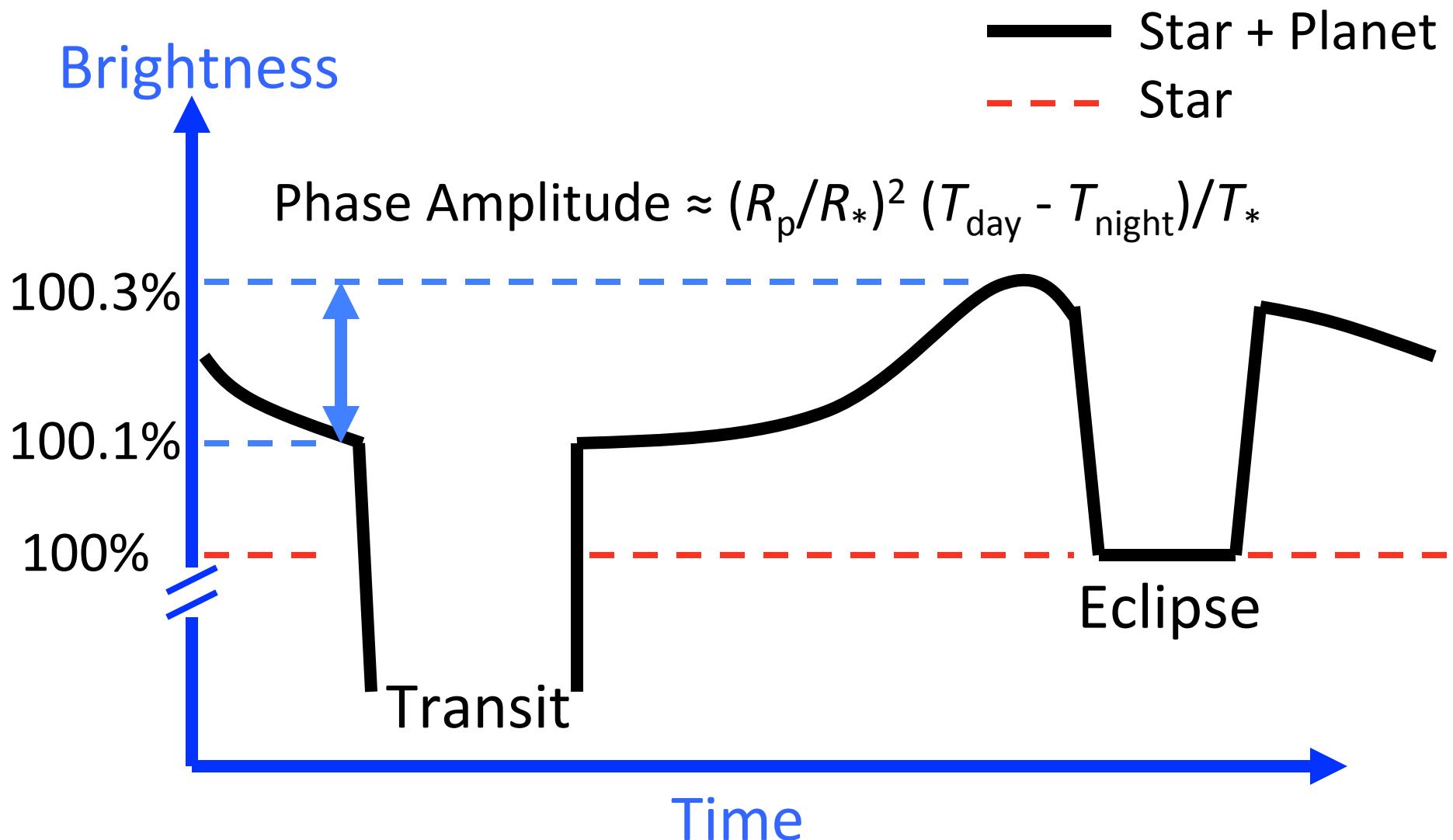
Area under curve tells us planet's dayside radiating temperature

Integrating noise is less damning than differentiating it

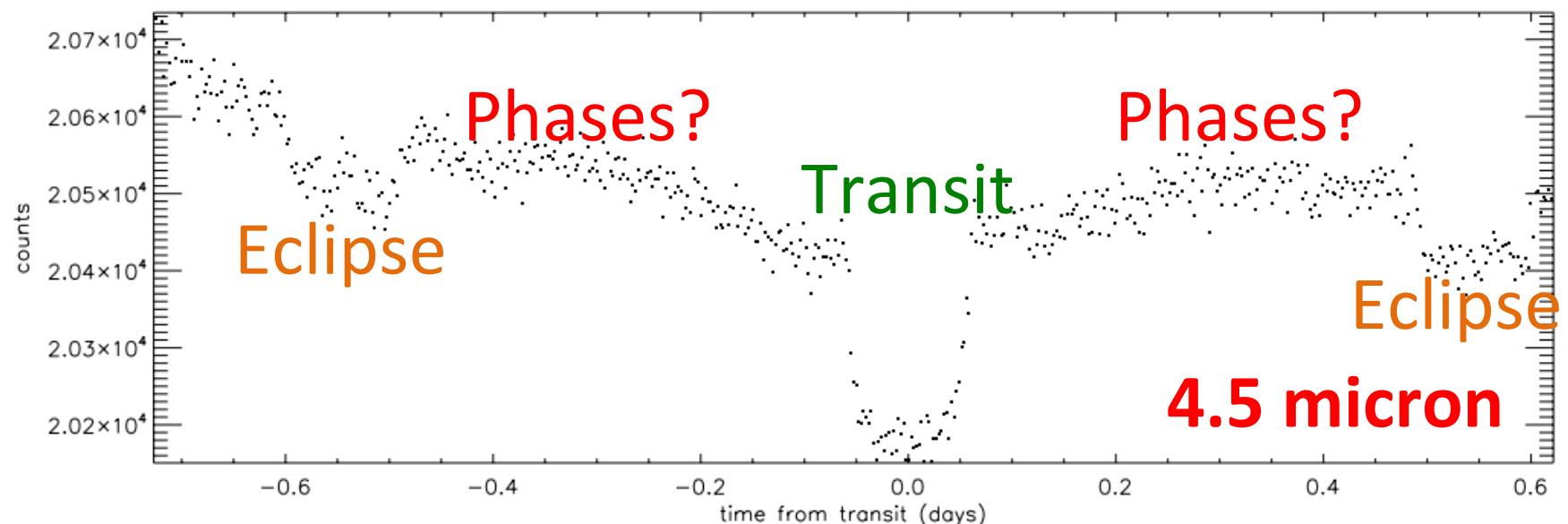
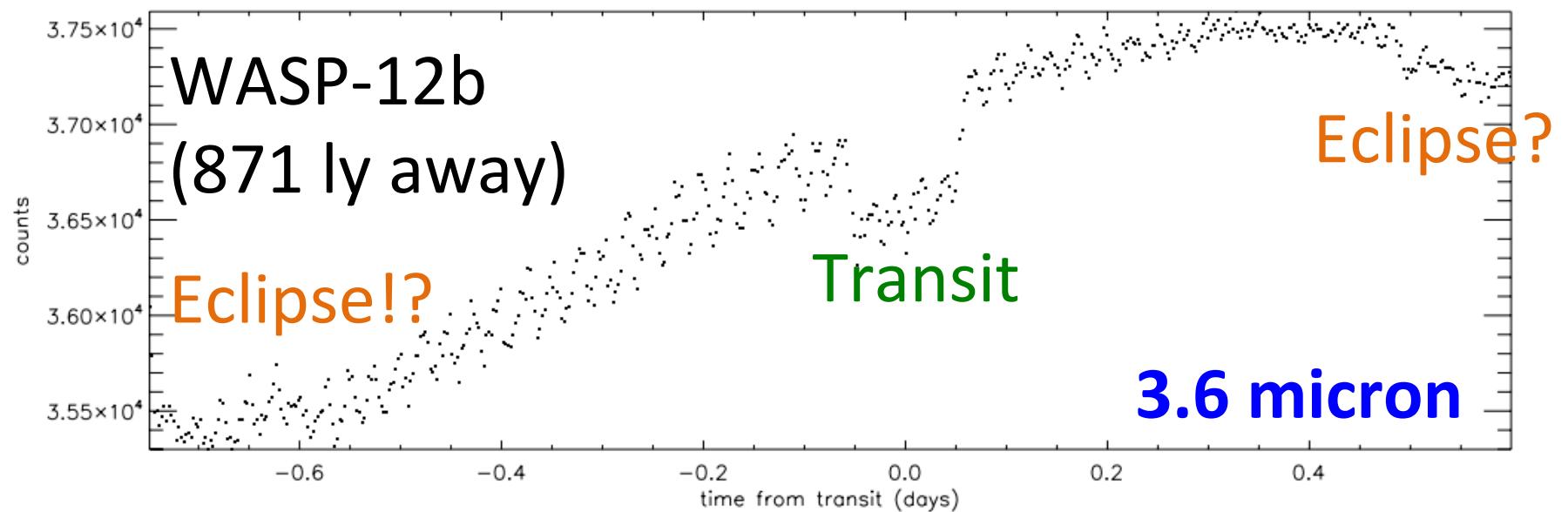
# Thermal Phases



# Thermal Phase Variations

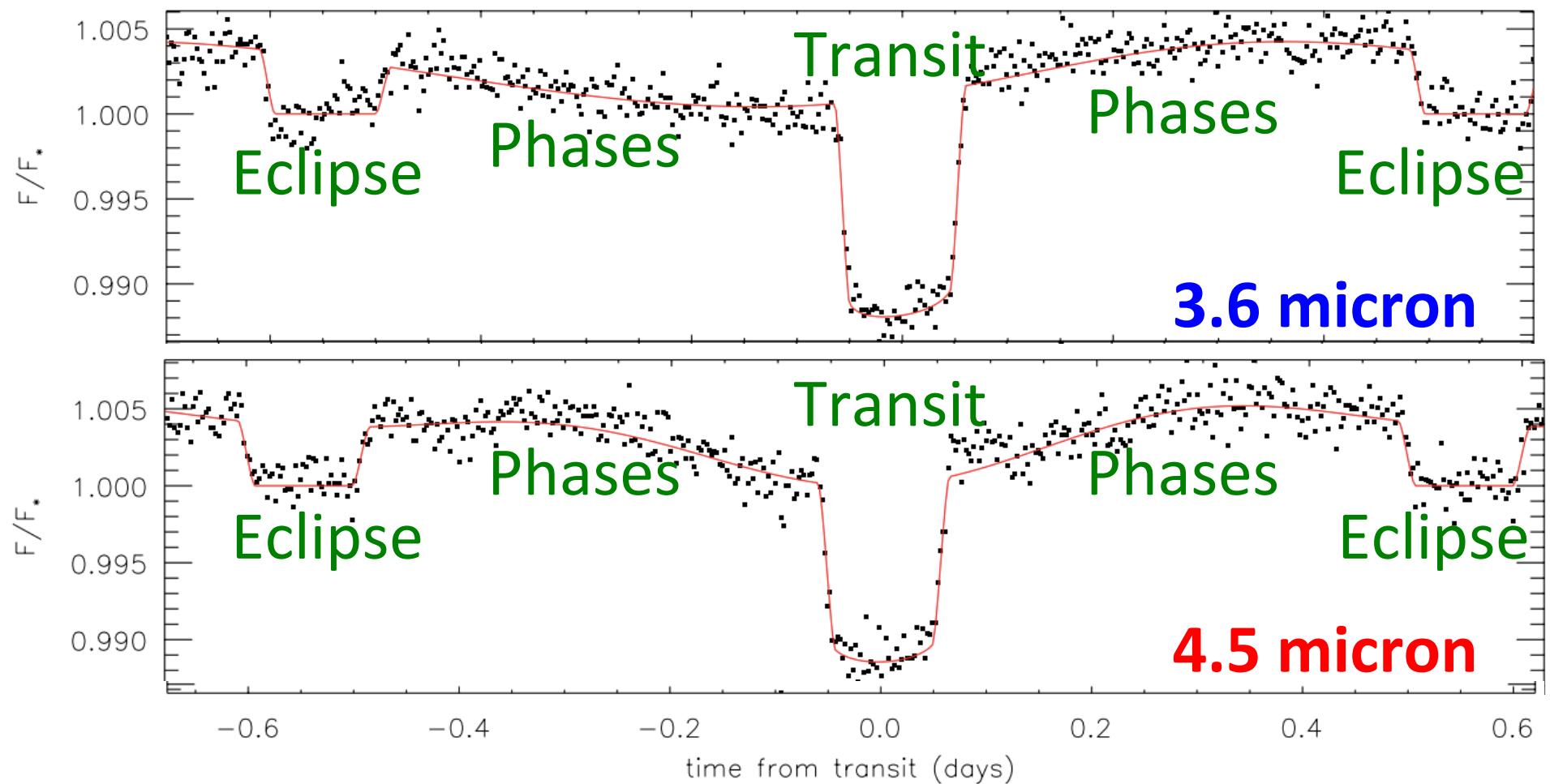


# Raw Spitzer Lightcurves



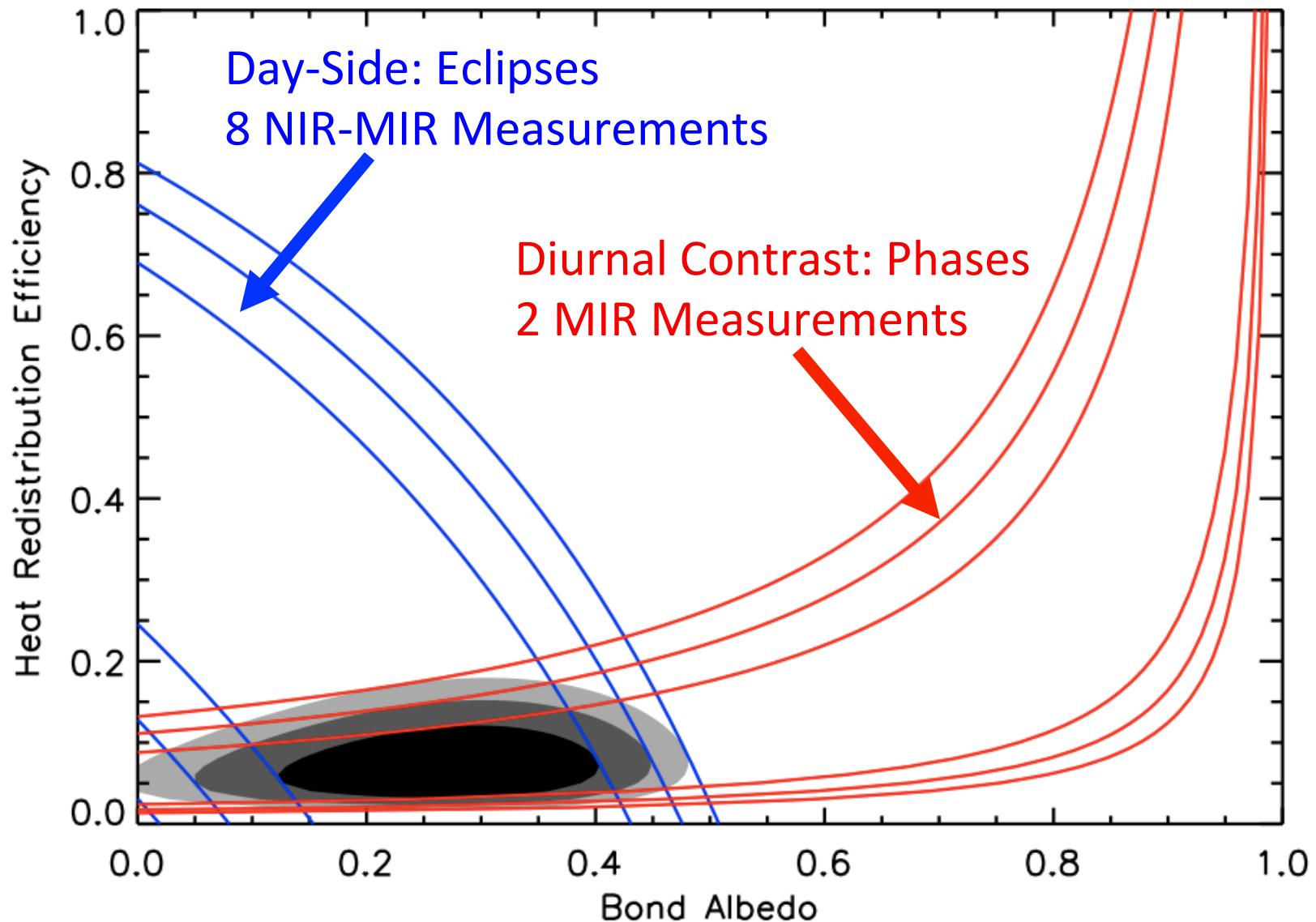
Cowan + Shekhtman+ (2012)

# After Running Enormous Fit...



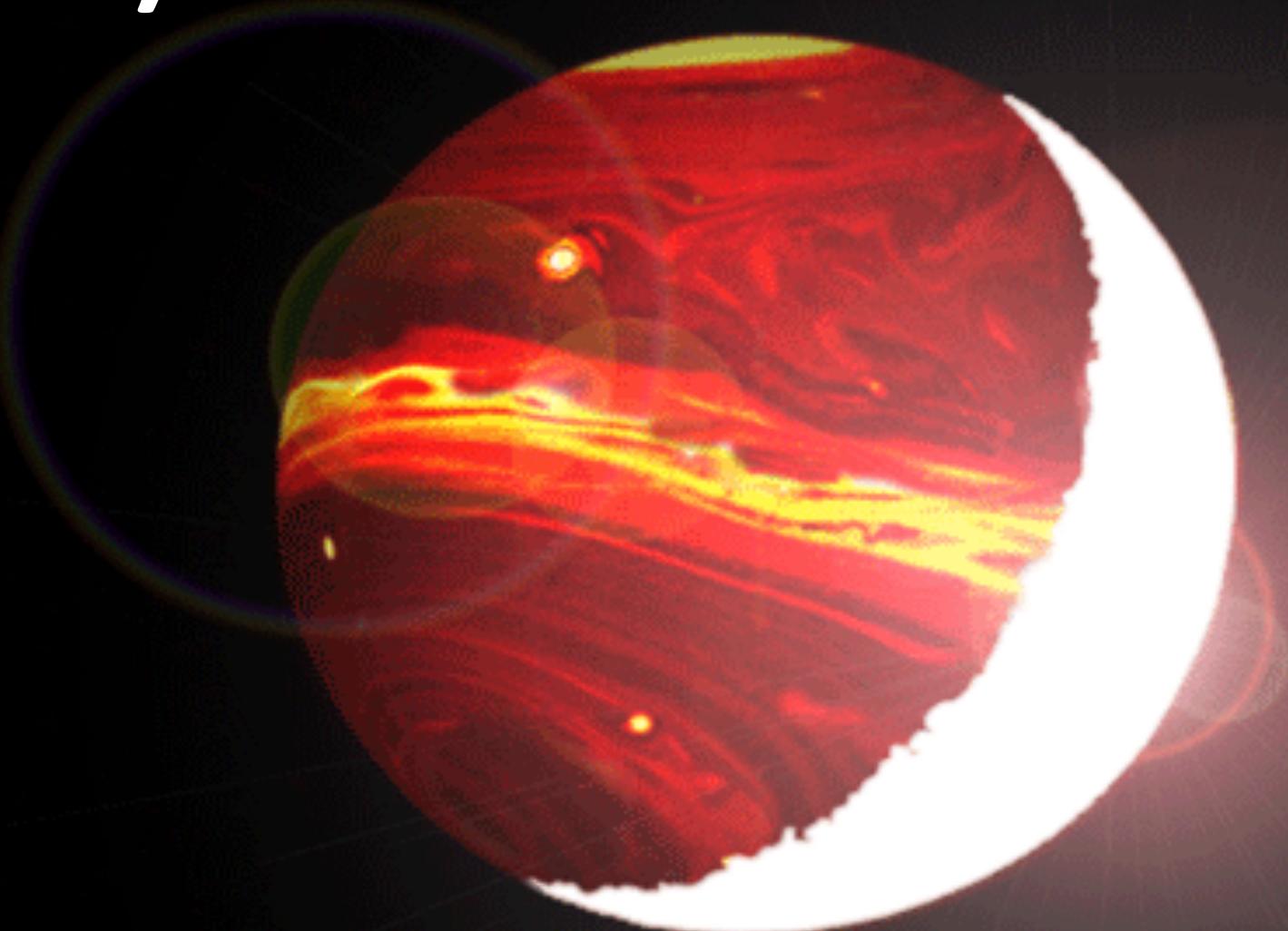
Cowan + Shekhtman+ (2012)

# WASP-12b is Bad at Moving Heat



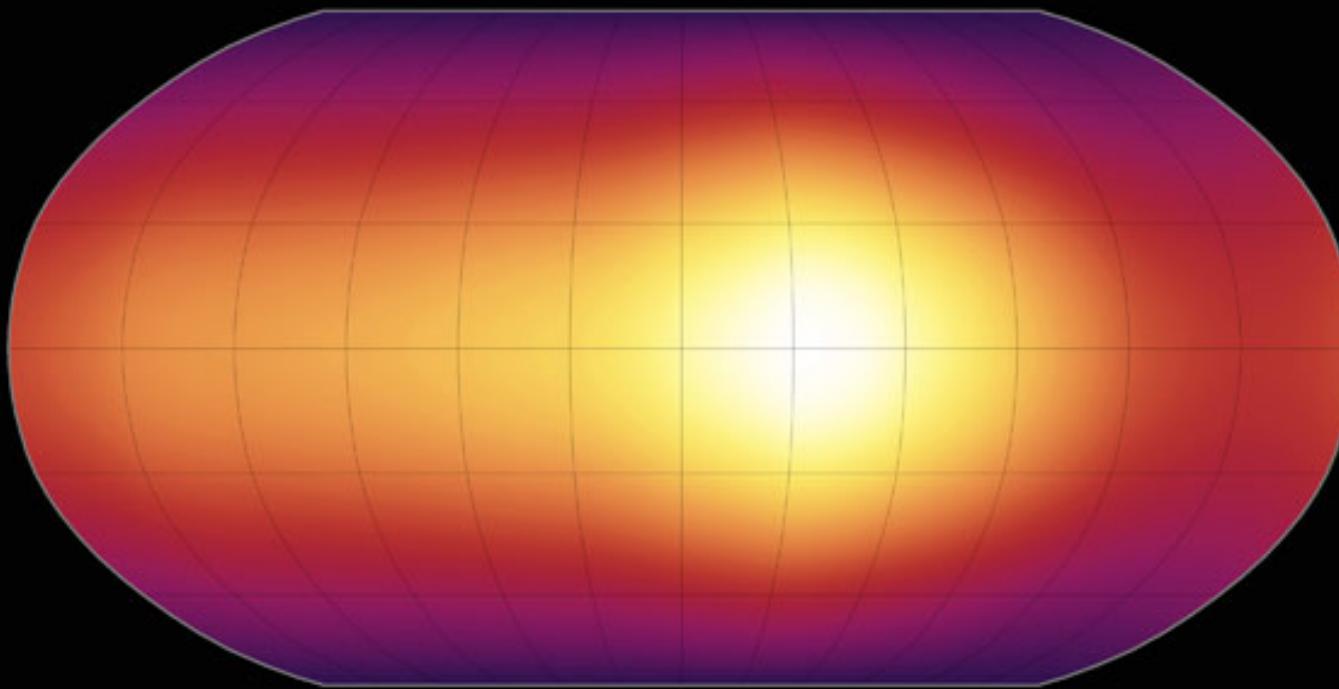
Cowan + Shekhtman+ (2012)

## 2) HEAT TRANSPORT



# Thermal Phase Mapping

HD 189733b (63 ly away)



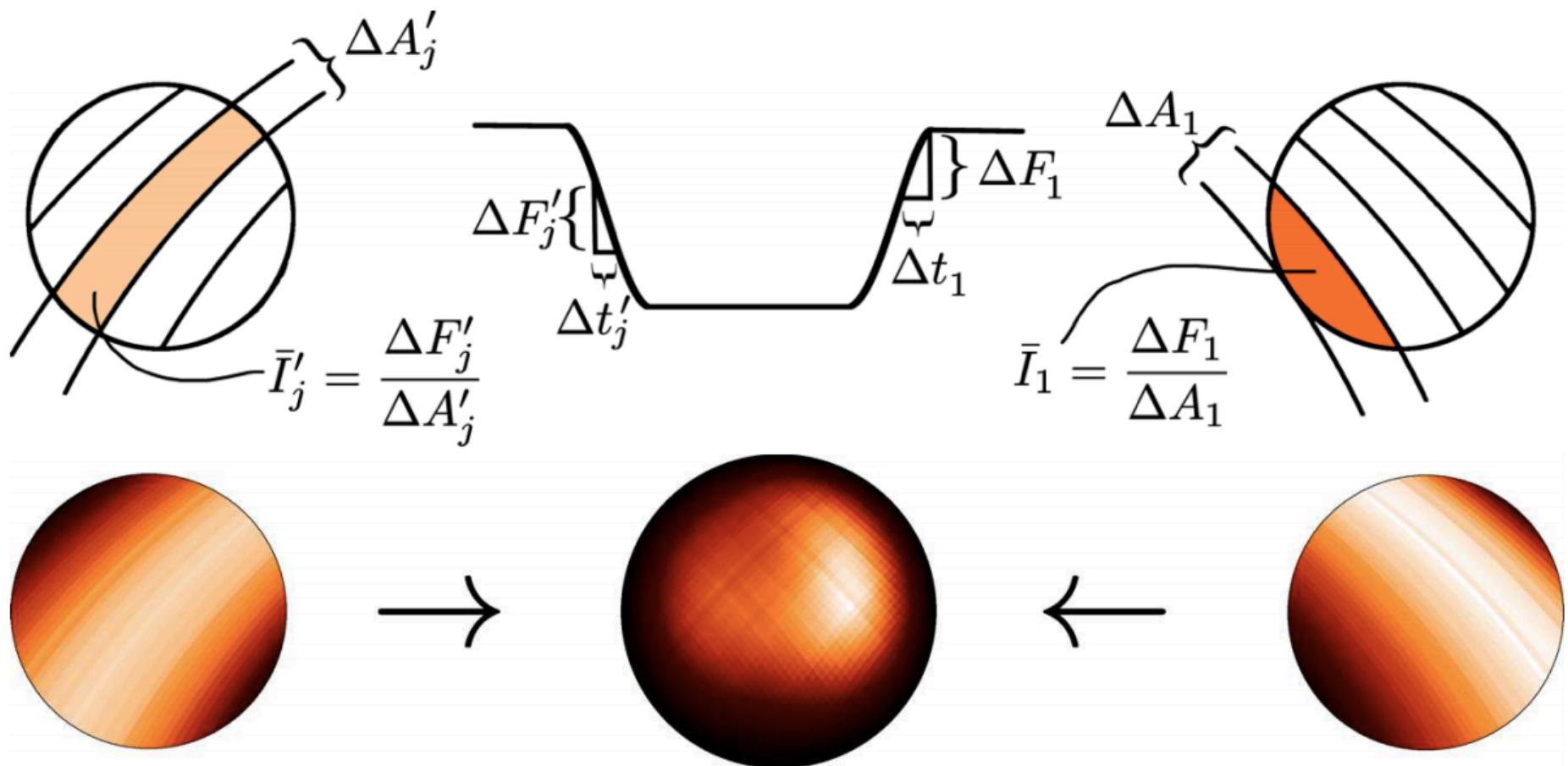
N-S Part of map is made up

Knutson + Cowan+ (2007)

Cowan & Agol (2008)

Cowan, Fuentes & Haggard (2013)

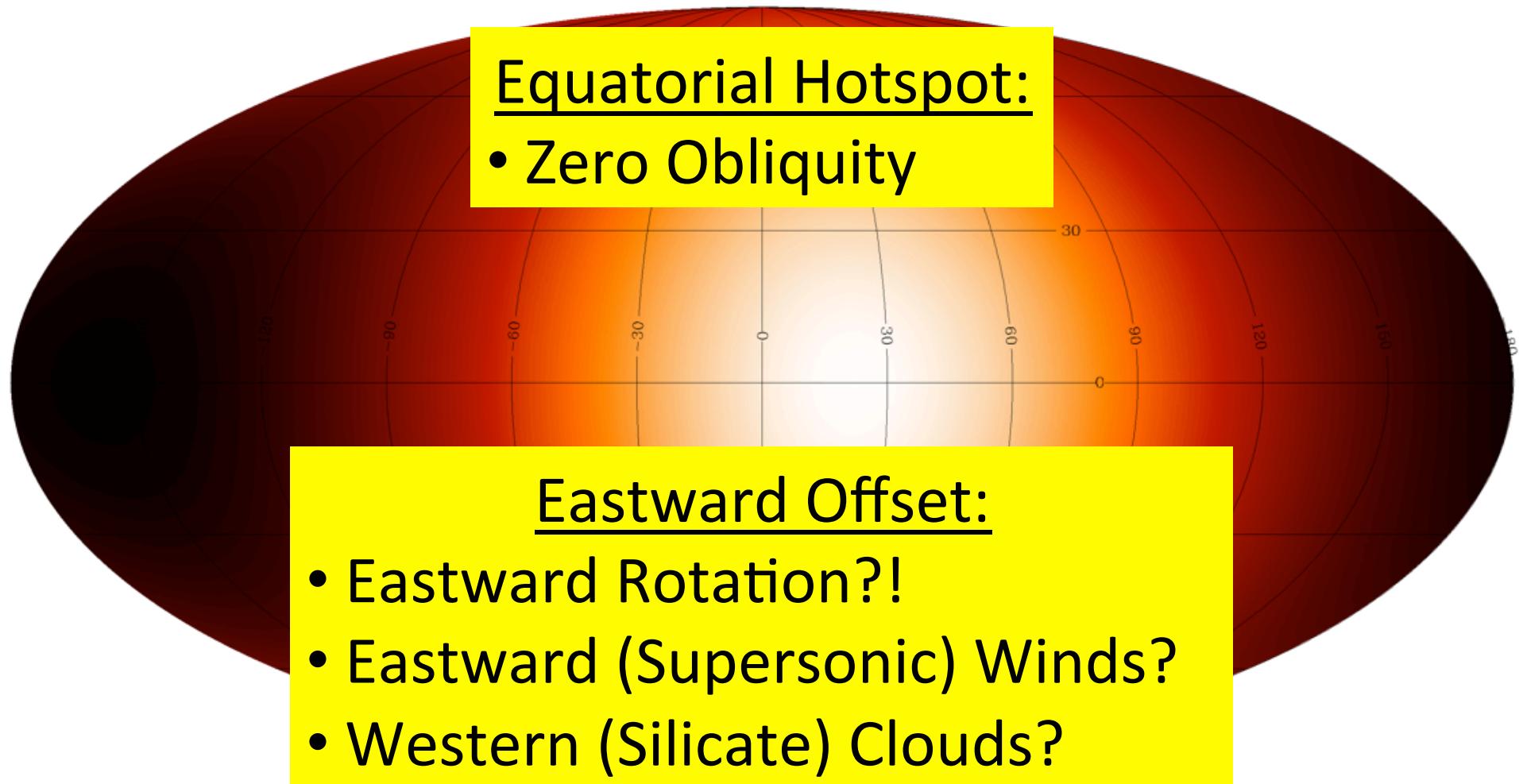
# Thermal Eclipse Mapping



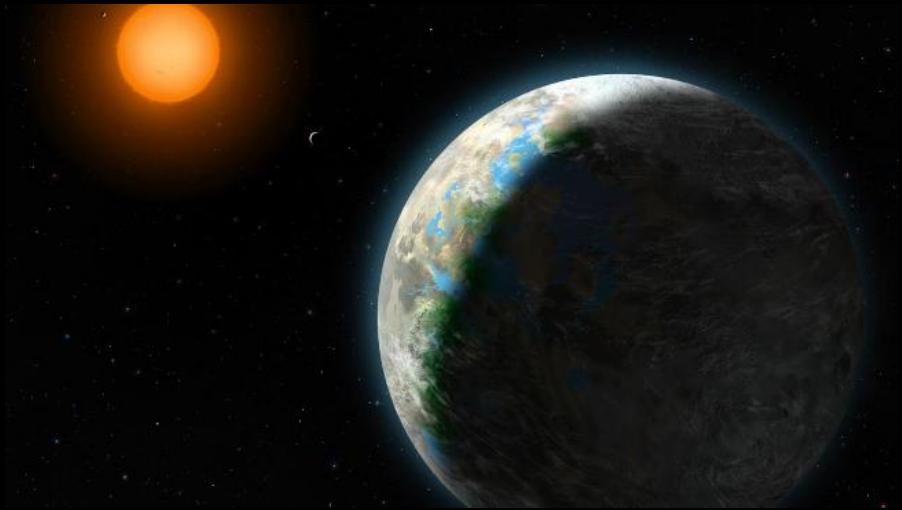
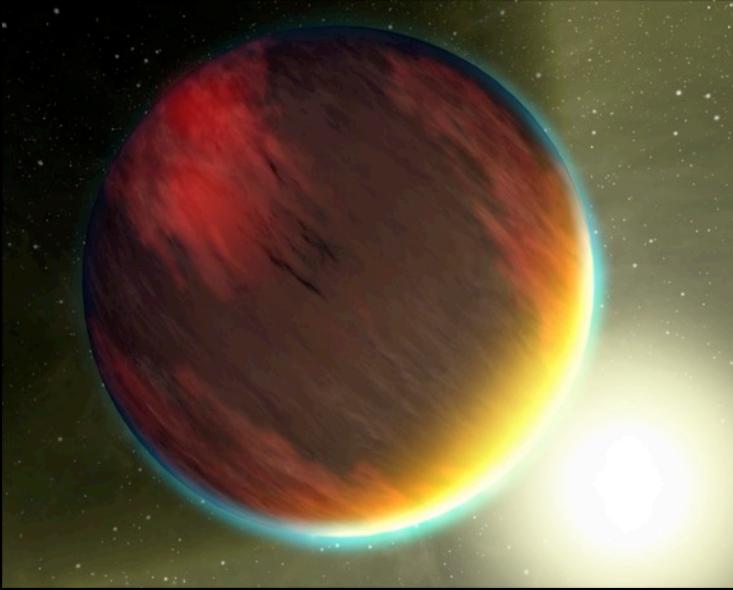
HD 189733b  
(63 ly away)

Majeau, Agol & Cowan (2012)

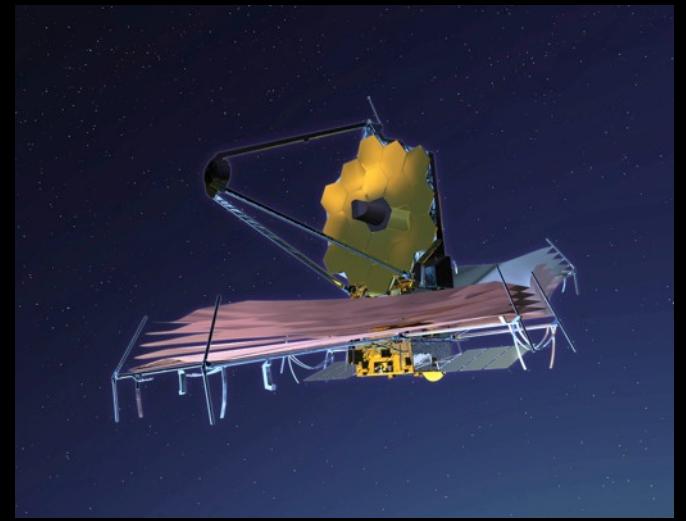
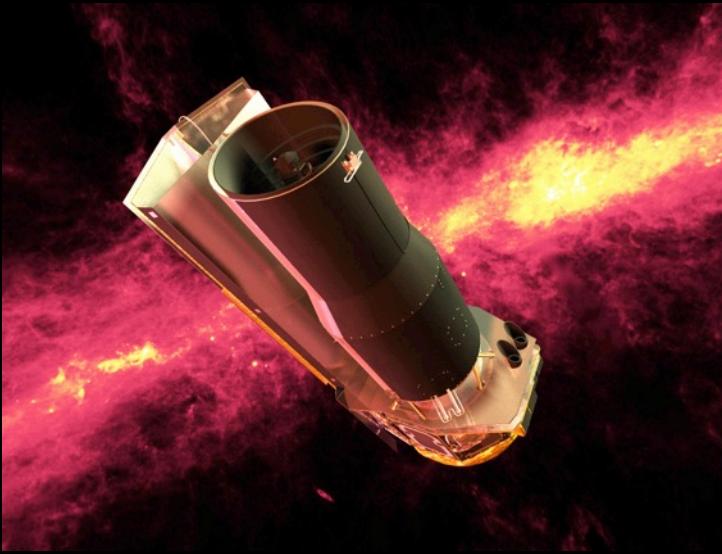
# Eclipse + Phase Mapping



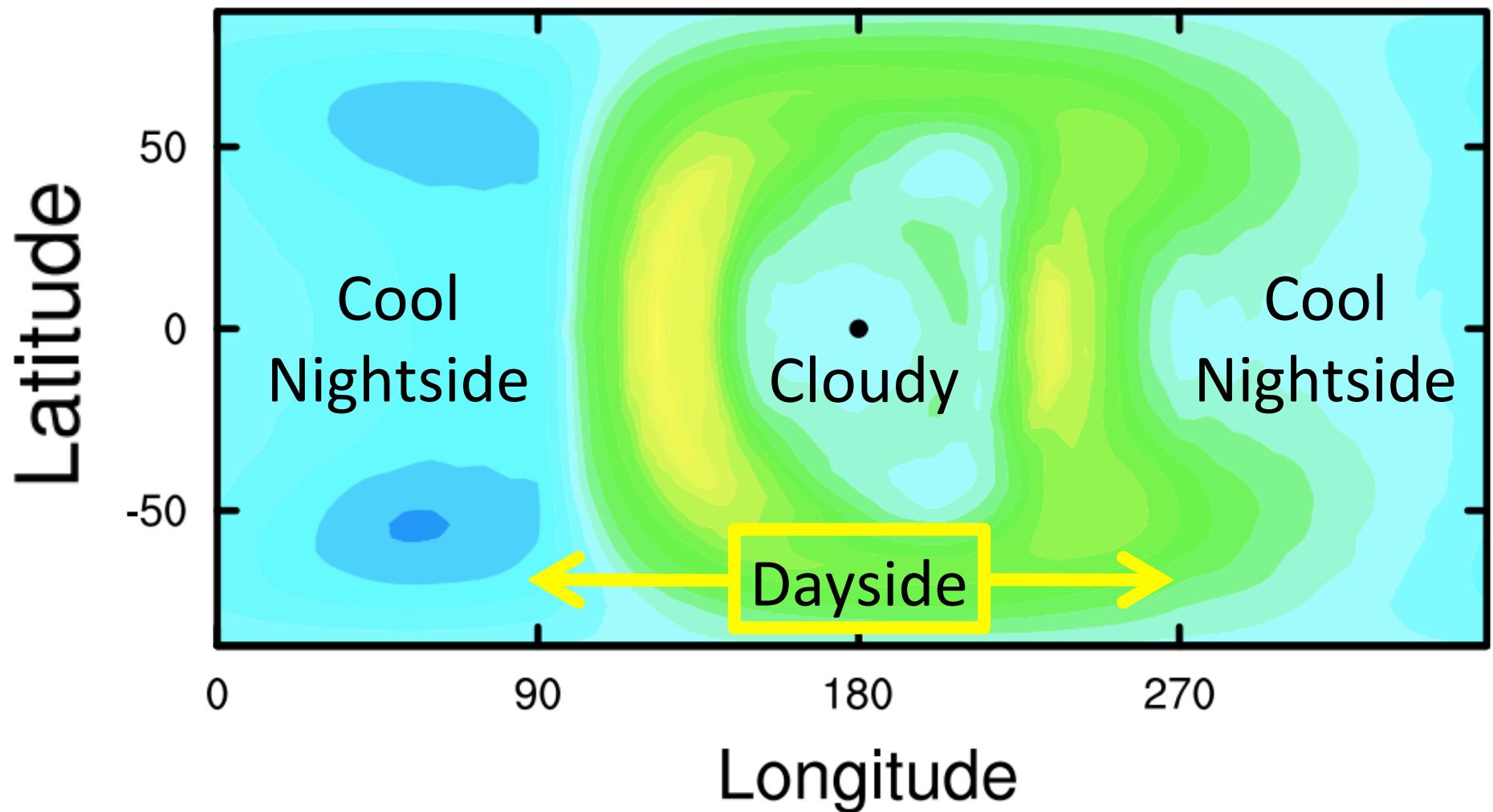
Majeau, Agol & Cowan (2012)



HOT JUPITERS → SUPER-EARTHS

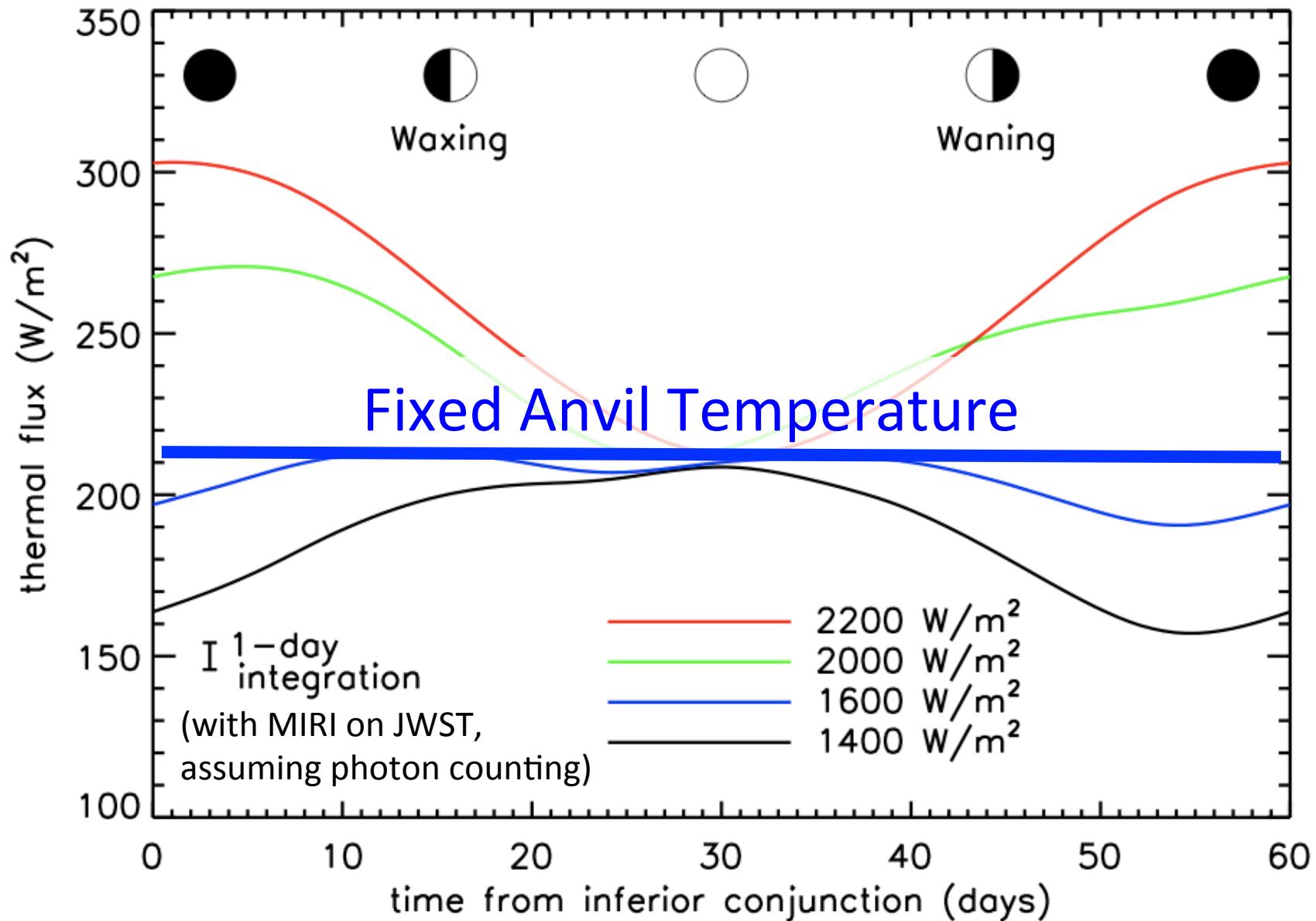


# Simulated Thermal Map of a Tidally-Locked Super-Earth



Yang, Cowan & Abbot (2013)

# Higher Insolation → Brighter Nightside

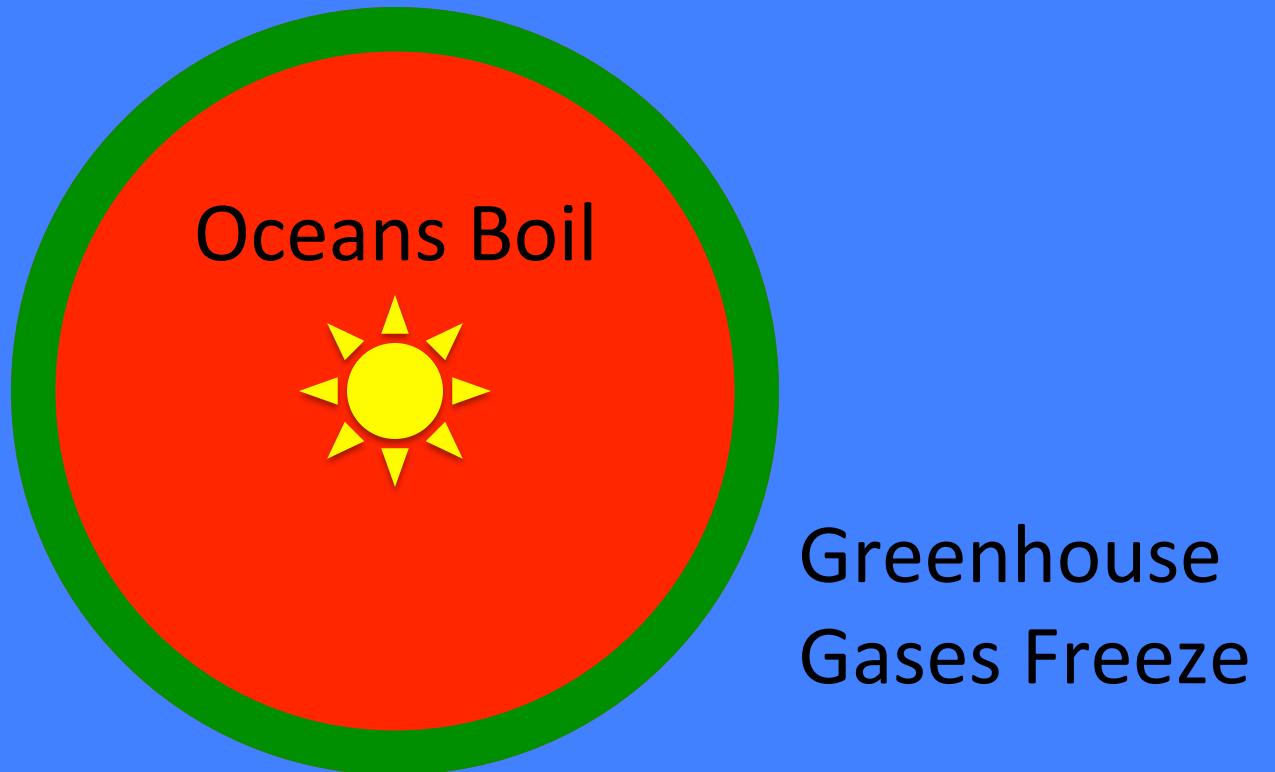


Yang, Cowan & Abbot (2013)



### **3) GREENHOUSE INVENTORY**

# The Habitable Zone

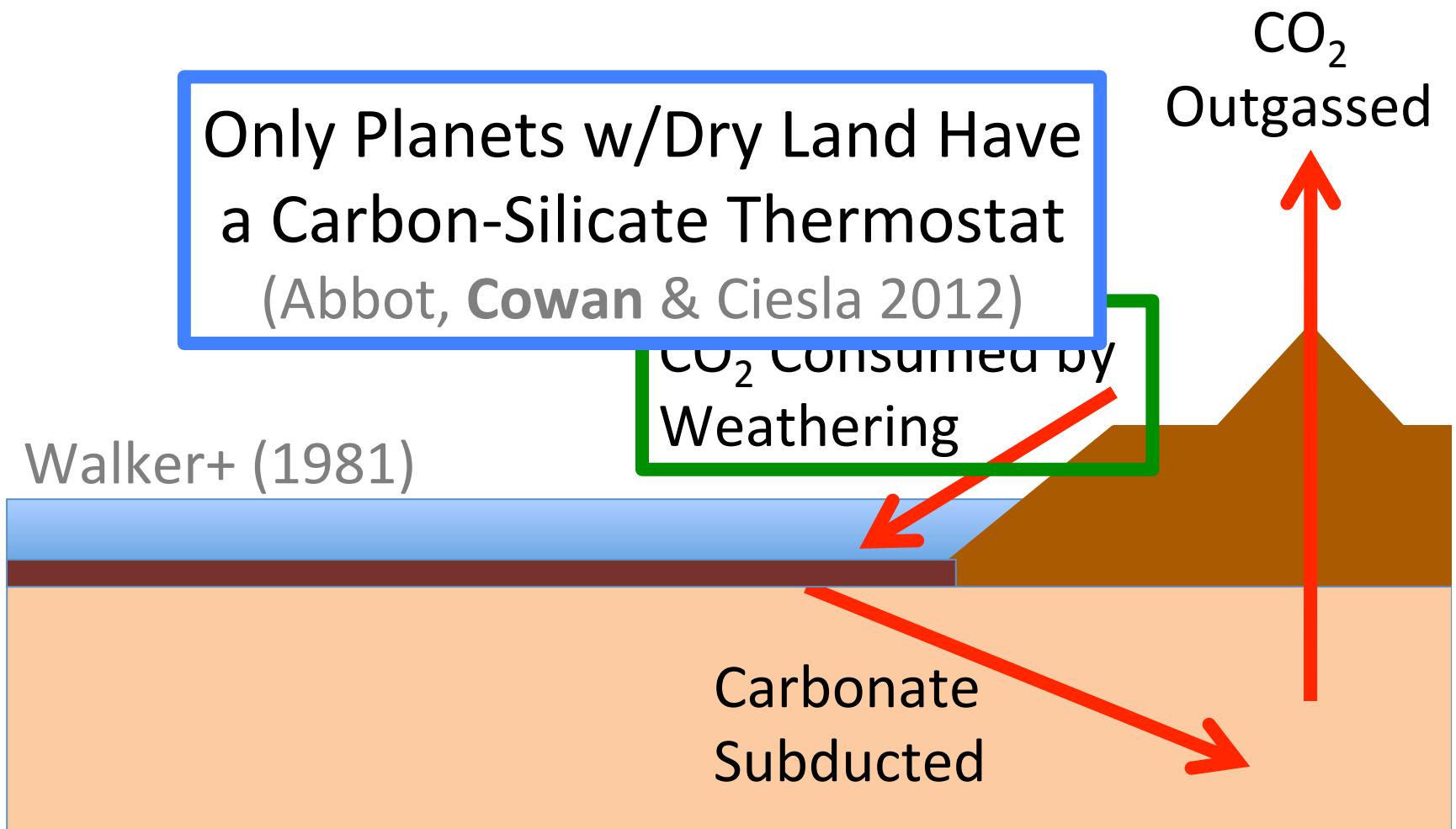


Huang (1959), Hart (1979)

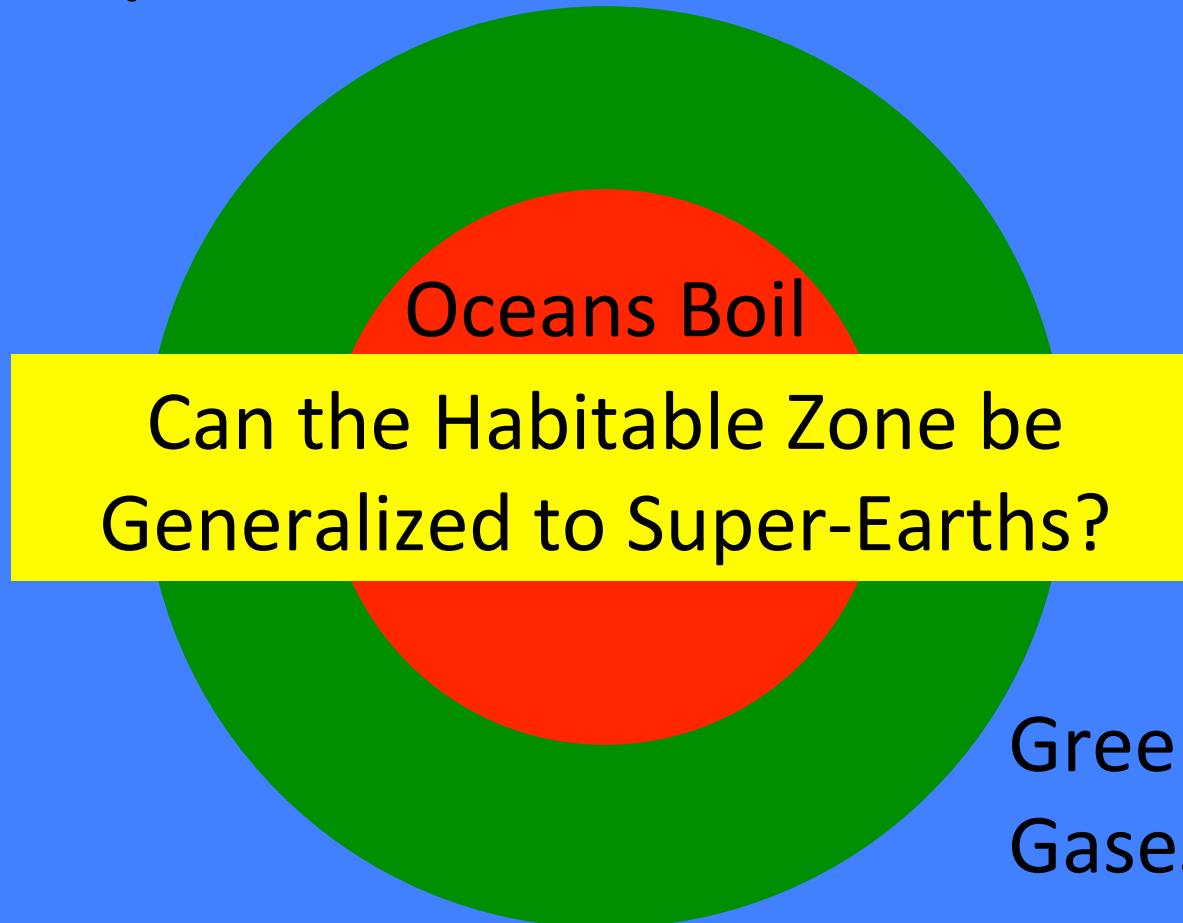
# Earth's Deep Carbon Cycle acts like a Thermostat

Only Planets w/Dry Land Have  
a Carbon-Silicate Thermostat  
(Abbot, Cowan & Ciesla 2012)

Walker+ (1981)



# The Habitable Zone (for planets with a thermostat)



Kasting+ (1993), Abe (1993)

# What *is* a Super-Earth?



Radius = 2x Earth's

**Area = 4x Earth's**

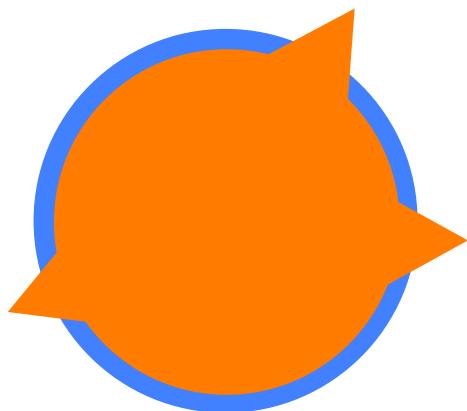
Mass = 10x Earth's

**Water = 10x Earth's**

Gravity = 2.5x Earth's  
**Earth**

**Topography = 0.4x Earth's**

# Super-Earths Should be Inundated



Earth



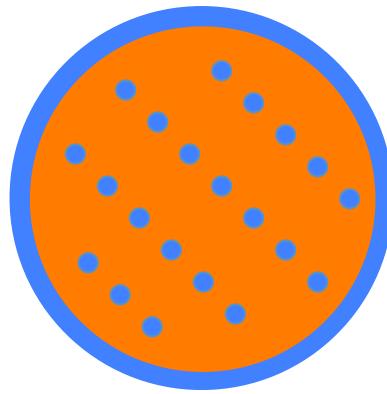
Super-Earth

No Dry Land

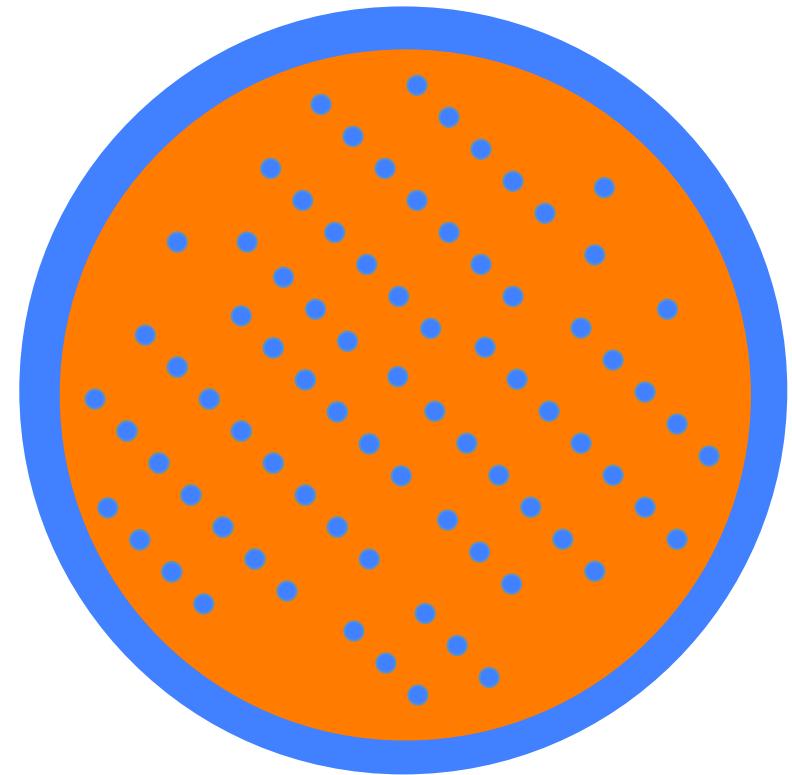
→ No Thermostat

→ Narrow Habitable Zone

# There Be Water in Them Rocks!

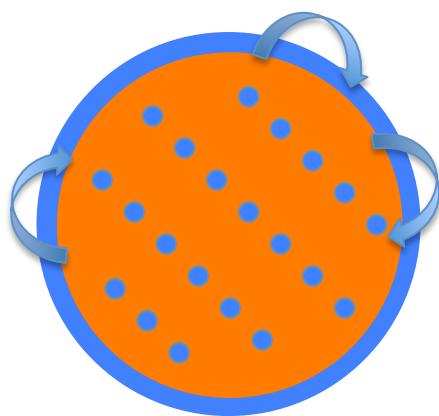


Earth

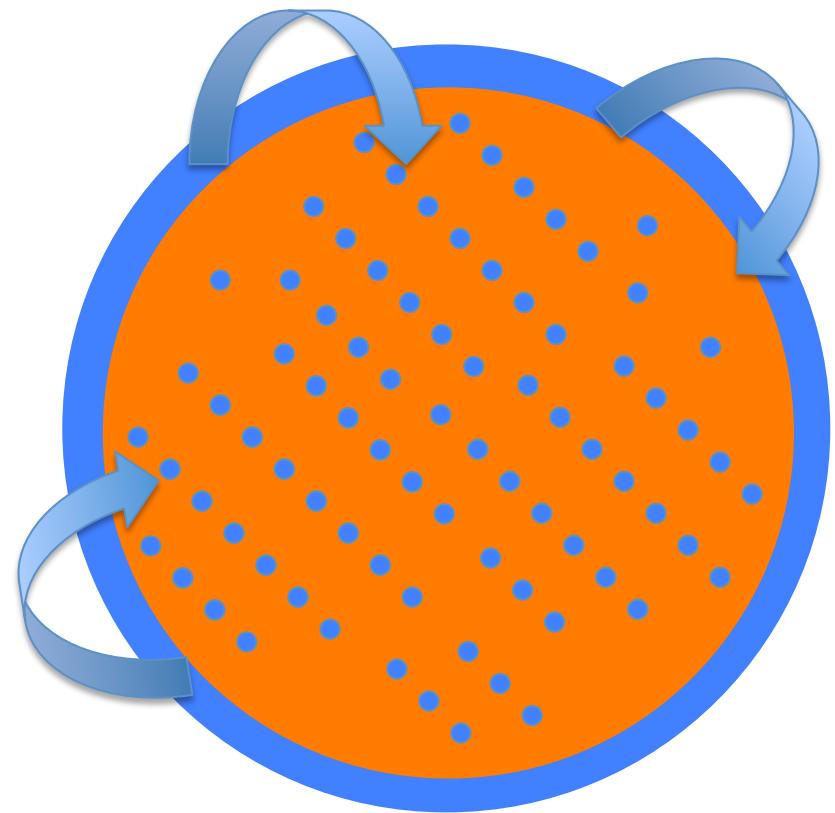


Super-Earth

# It Moves!



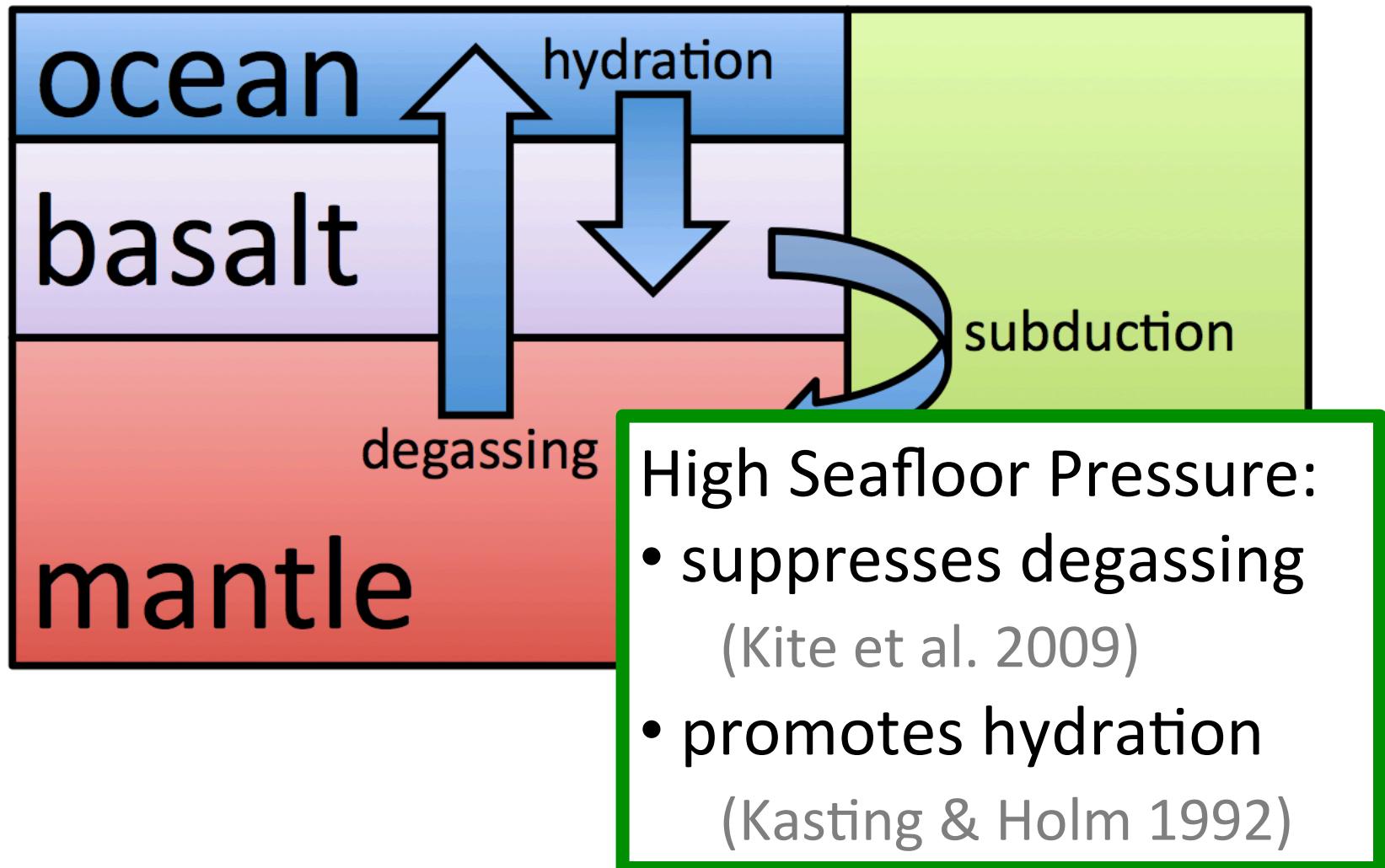
Earth



Super-Earth

# The Deep Water Cycle

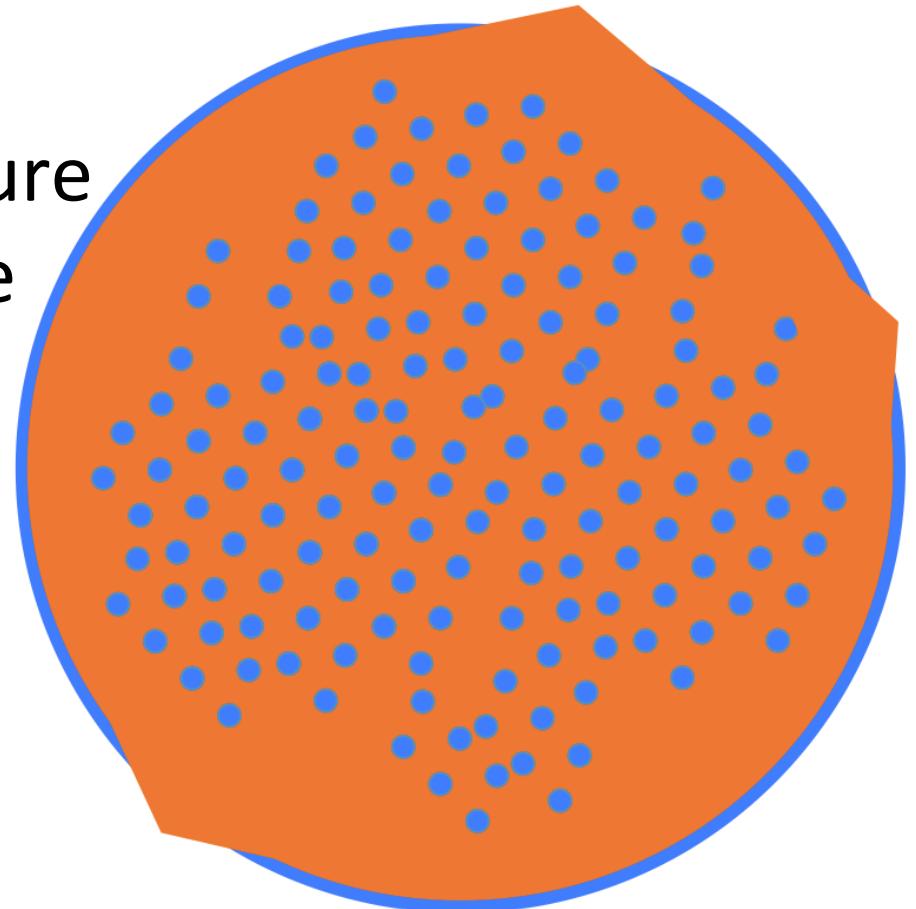
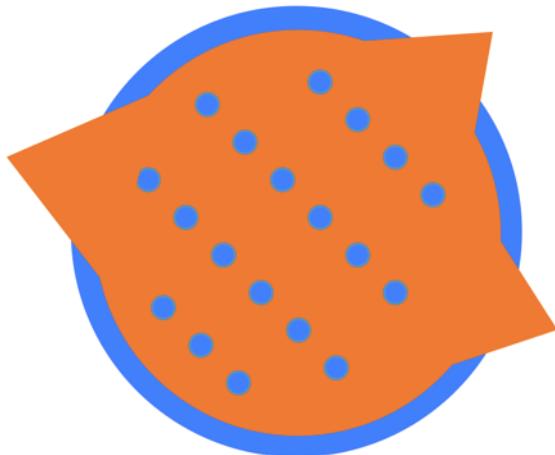
Cowan & Abbot (2014)



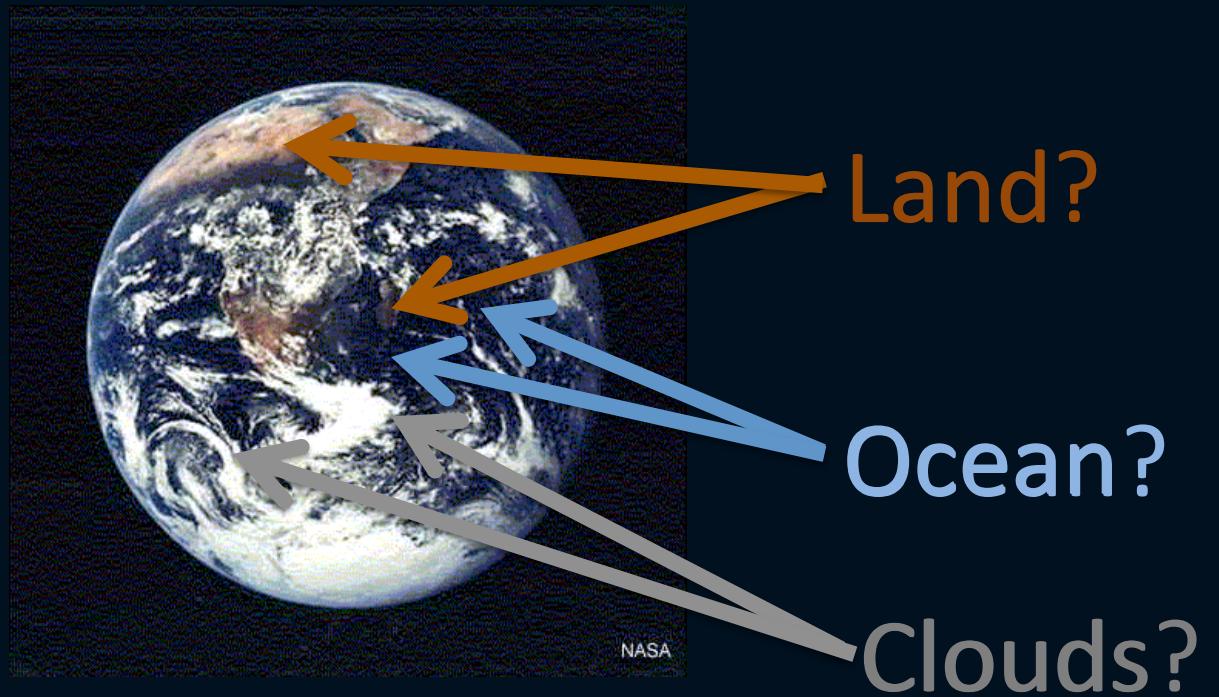
# Super-Earths Need Not be Waterworlds

Super-Earths have High Gravity

- Shallow Ocean Basins
- More Water per Area
- Higher Seafloor Pressure
- More Water in Mantle
- Shallow Oceans



## 4) GROUND TRUTH



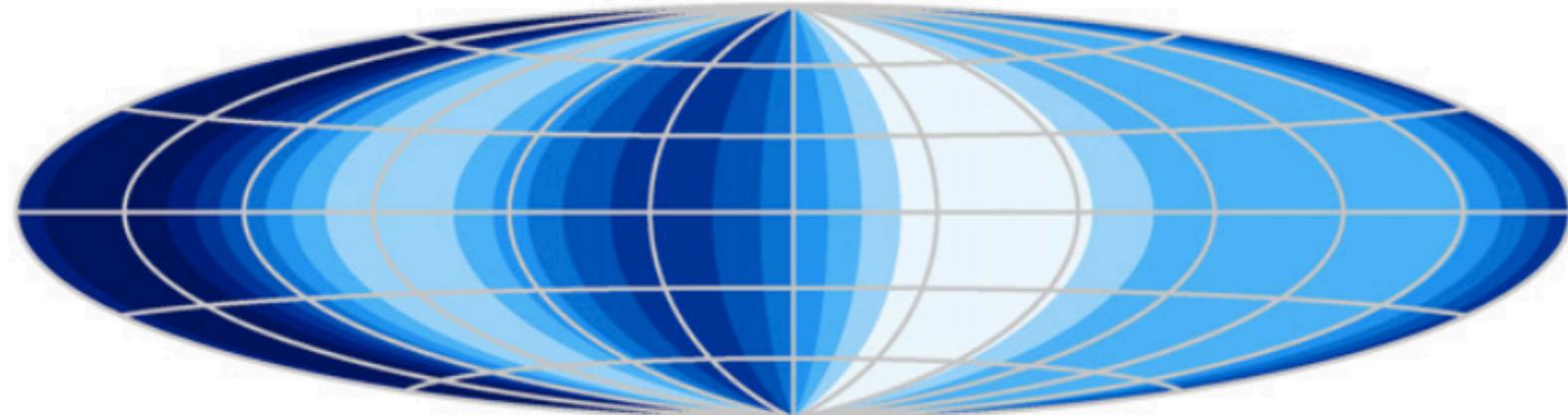
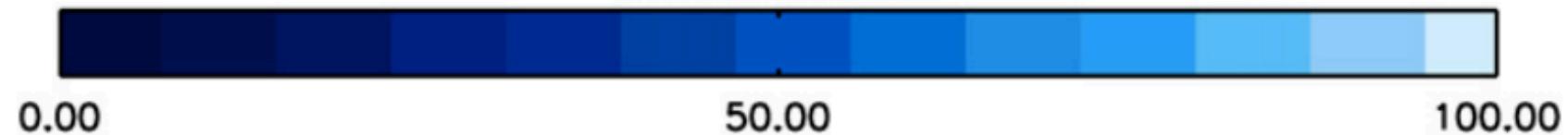
# Earth as seen by:

- (1) Planetary Rotation Rate (Pallé+2008)
- (2) Number of Surfaces (Cowan+2009, 2011)
- (3) Surface Spectra (Cowan & Strait 2013)
- (4) Surface Maps (Cowan+2009, 2011)

# A Crude Map of Earth

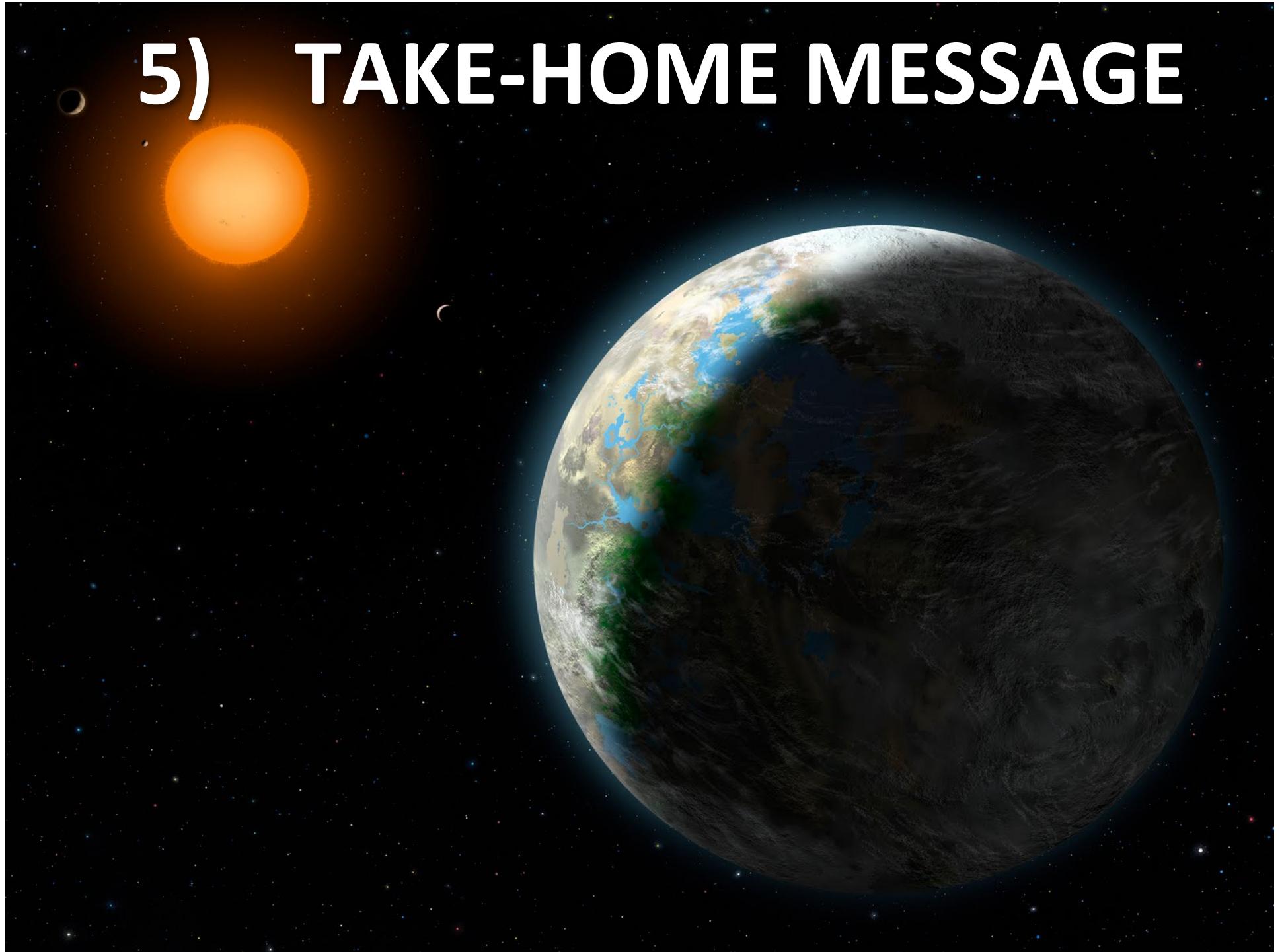


Percent Land



(Cowan+ 2009)

# 5) TAKE-HOME MESSAGE



(1) Planetary Climate is Largely Determined by a Few Parameters

(2) Parameters are Hard to Predict, but *Can Be Measured*

(3) Coarse Exoplanet Observations + Detailed Solar System Observations = *Better Planetary Models*

# Questions?

